THE EFFECTS OF LAND USE ON STREAM COMMUNITIES IN HIGHLAND TROPICAL NIGERIA

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Contents

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Abstract

Globally, stream invertebrate communities have been shown to respond to habitat degradation as a result of land use changes. The effects of land use changes on stream communities have been well documented in temperate regions, however, their effects in the tropics are relatively unknown, particularly where land use activities can differ markedly (e.g., tea, maize and Eucalyptus plantations). To understand how land use affects tropical highland Nigerian stream communities, I surveyed 55 second and third order streams across four land use categories, ranging from continuous tropical montane forest to intensive crops/pasture. Streams were sampled in the dry season (October to March) for physico-chemical parameters (i.e., temperature, pH, conductivity, turbidity, current velocity, channel morphometry and riparian characteristics) and ecological characteristics (i.e., fine particulate organic matter [FPOM], coarse particulate organic matter [CPOM], algae and benthic invertebrates). Water temperature in all streams was high (up to 25^{o}C) while levels of dissolved oxygen were frequently low (15–79 %). Physico-chemical conditions varied across land uses with continuous forested streams being cooler, with higher dissolved oxygen, larger bed substrate and more stable channels. Similarly, benthic invertebrate communities showed a strong response with the highest taxonomic diversity in forested streams and the lowest in streams within intensive crops (e.g., cabbage crops). Several of the taxa which occurred in forested streams (e.g., the mayflies Heptageniidae and Oligoneuridae and brachyuran crabs) were rare or absent in streams with more intensive land use. In contrast, damselflies and several true bugs (e.g., Notonectidae and Corixidae) were rare in forested streams but more common in other land uses. In order to test land use impacts on stream processes leaf litter decomposition experiments were carried out in nine streams, three in forest, three in tea plantations and three in maize fields. Leaf breakdown rates were slow compared with other reports for tropical streams, however leaves in forested streams broke down significantly faster (on a degree day basis) than in other land uses. This faster break down seemed to be driven by greater shredder densities in forested streams. Significantly lower densities of invertebrates were found in leaf bags incubated in streams draining tea plantation and maize fields than in forest streams. In the same nine streams food web components were sampled and analysed using gut content and stable isotope (N and C) analyses. Stream food webs in continuous forest were more complex than plantation and maize field streams. Stable isotope analysis indicated that primary consumers assimilated a mixture of autochthonous and allochthonous carbon resources, but the proportion varied among sites.

Overall, my results suggest that in Nigerian highland tropical streams more intensive land use activities strongly affect the diversity and composition of benthic stream communities and ecosystem function, in similar ways to those reported in temperate streams.

Chapter one

General introduction

Introduction

Freshwater systems

Globally, freshwater systems account for a disproportionately high proportion of biological diversity (Boulton *et al.*, 2008; Dudgeon, 2010). This high biodiversity is often supported, and probably enhanced, by the exchange of resources between terrestrial and aquatic environments (Wallace *et al.*, 1997). An increasing number of studies have demonstrated the importance of ecological linkages between land and water ecosystems (Crown *et al.*, 1995; Nakano and Murakami, 2000; Baxter *et al.*, 2005; Shawn and Michel, 2008). For example, in Borneo tropical rain forest fruits, leaves and other plant litter from the forest represent the main organic inputs to aquatic systems and are the chief source of food for plant eating macroinvertebrates and fish (Edward, 1994). Furthermore the emergence of adult insects could represent a considerable transfer of energy from water to land and aquatic insects may therefore be an important food source for terrestrial consumers such as bats, birds and spiders (Baxter *et al.*, 2005). Several studies have shown that stream insects can provide an important subsidy to riparian invertebrate predators (Baxter *et al.*, 2004; Briers *et al.*, 2005; Paetzold *et al.*, 2006; Marczak and Richardson, 2007; Burdon and Harding, 2008).

The link between terrestrial and freshwater ecosystems can also result in freshwater systems being vulnerable to human-induced stresses on one or both ecosystems. Major changes to the rates of ecosystem processes, through excessive nutrient loading or the disruption of essential nutrient cycles (Vitousek *et al.*, 1997) can have strong effects on freshwaters and some researchers have suggested that freshwater ecosystems are the most threatened ecosystems on the planet (Abramovitz, 1996; Malmqvist and Rundle, 2002; Postel and Richter, 2003; Dudgeon and Chan, 2006). Worldwide, stream communities have been subjected to varying degrees of degradation as a result of changes in land use; in particular the degradation of low land rivers by prolonged agricultural activity, is receiving increasing recognition as a global problem (Harding *et al.*, 1999). The conversion of land from one use to another affects stream ecosystems in a number of ways, such as changes to nutrient loadings (Allan *et al.*, 1997), solar energy fluxes (Hicks, 1997), hydrology (Quinn *et al.*, 1997) and decomposition rates of organic matter (Niyogi *et al.*, 2003; Ferreira *et al.*, 2006; Gulis *et al.*, 2006).

Tropical land use and its effects on streams

Globally, tropical streams are under increasing pressure from human development and land use (Grove, 1985; Dudgeon, 2000; Dudgeon and Chan, 2006; Strayer, 2006; Dudgeon *et al.*, 2010). However, in the tropics some human land use activities differ from those occurring in temperate regions. For example, in many developing tropical nations farming practices often disregard environmental impacts, so overgrazing is common, and the use of fire to burn off forest and clear land for development can be a standard practice. Consequently, deforestation is a widespread issue in tropical regions (Jones *et al.*, 2001; Couceiro *et al.*, 2007). In Nigeria, many rural villages rely on firewood for cooking and heating and plantations of *Eucalyptus* spp.*, Parkia* spp. *and Delonix regia* are commonly grown and harvested in some areas. The mechanism by which some of these land use activities influence stream communities are well known in temperate regions, however their effects on tropical stream and rivers are not well understood. Other practices, common to temperate regions as well, such as mining, quarrying, damming rivers for hydroelectric power and irrigation are all major sources of concern in tropical African countries (Leveque *et al.*, 1991). As land use change continues unabated in the tropics, the potential loss of biodiversity is outpacing our ability to understand its implications.

Many stream ecosystem functions such as nutrient cycling, and decomposition may differ in tropical as compared with temperate streams and are certain to change with land use (Tripler *et al.*, 2006). However, our understanding of such functions is limited in tropical streams (Encalada *et al.*, 2010). For example, Kasangani *et al.* (2007) documented sediment loading due to forest conversion to agricultural land in Uganda, and found agricultural sites and deforested sites generally had the highest turbidity, total dissolved solids (TDS) and conductivity values, whereas low turbidity and conductivity were recorded in forested and forest boundary sites. An assessment of nitrogen cycling in Venezuela highlighted the importance of anthropogenic sedimentation in increasing denitrification rates in tropical streams (Solomon *et al.*, 2009).

Much of the high diversity associated with freshwaters probably occurs in the tropics, however, despite their importance surprisingly little has been published on the benthic ecology of tropical ecosystems (Flecker, 1997; Kasangaki *et al.*, 2007; Dudgeon, 2008). This is in strong contrast to temperate streams which have been well studied. The paucity of research on tropical freshwaters is in part probably due to the low numbers of freshwater ecologists in these regions in comparison with North America and Europe. It is apparent that

a better knowledge of lotic ecosystem dynamics in West Africa will improve only if the scientific community is able to increase its research effort in this region (Leveque, 1991).

Tropical streams experience very different physico-chemical and climatic conditions from temperate streams. They typically have higher average water temperatures and low thermal variation and are exposed to seasonal monsoonal rains, which create highly variable flow regimes (Dudgeon, 2008). Although flow regimes are highly variable, they are reasonably seasonally predictable. The seasonal predictability may result in some adaptation to this regular disturbance. The overall effects of these different conditions have not been well explored in terms of stream fauna, although we might expect organisms to complete their faster life cycles faster and that their development is synchronised to seasonal high and low flows. Furthermore, rivers draining undisturbed tropical catchments are typically low in nutrients and consequently primary production is usually low (Douglas *et al.*, 2005; though see Dudgeon *et al.*, 2010). For example, phytoplankton biomass in the main stems of the larger Orinoco and Amazon rivers have been shown to be low (Hamilton *et al.*, 1992; Lewis *et al.*, 2001; Douglas *et al.*, 2005).

Dudgeon (2008) suggested that there is no such thing as a "typical" tropical stream because of the diversity in flow patterns, and landscapes. The latter can be as varied as evergreen rainforest, deciduous seasonal forests, high-altitude grasslands, or even deserts (Boyero *et al.*, 2009). This diversity suggests that making generalizations about tropical streams may be of limited value, however, it also indicates that much is to be learned about stream ecology in tropical regions.

Most studies of tropical streams have been conducted by a small number of research groups in just a few geographic regions particularly in Costa Rica (Genereux and Jordan, 2006), Hong Kong (Dudgeon *et al.*, 2006), Puerto Rico (Greathouse and Pringle, 2006), Australia (Downes *et al.*, 2006; Pearson and Boyero 2009), Venezuela (Penczak, 1991) and the Kakamega Forest of Western Kenya (Clausnitzer, 1999 and Dobson *et al*., 2002). This relatively limited geographical representation of running waters, further constrains our ability to understand and make generalizations about tropical regions (Boyero *et al.*, 2009).

Although current ecosystem models of streams and rivers have placed variable emphasis on the importance of in-stream primary production to aquatic food webs, recent research indicates that aquatic algae can be significant contributor to food webs in tropical rivers and streams (Douglas *et al.*, 2005; Dudgeon, 2008; Dudgeon *et al.*, 2010). Several studies on primary production in tropical streams suggest that rates of instream primary production are typically at least an order of magnititude greater than in comparable temperate

systems (Davies *et al.*, 2008). Much of the primary production within the channels of streams and rivers, particularly those with fast flowing water, is benthic rather than planktonic (Canfield and Hoyer, 1988; Lamberti and Steinman, 1997).

The distribution, biomass and production of aquatic plants are controlled by a number of factors, among which light availability is the most important (Boston and Hill, 1991; Hill, 1996). The amount of light required by different aquatic plants is not the same and there is evidence that light intensity is a major factor determining the composition of algal communities (Gosh and Gaur, 1994; Hill, 1996; Bixby *et al.*, 2003). Low diversity of chlorophytes seems typical of tropical streams as their chlorophyll requires higher light intensity than diatoms (Richardson, 1991; Hill *et al.*, 1995).

Another important source of energy for tropical streams is organic matter (such as leaves and wood) from the surrounding land. This constitutes the largest allochthonous source of energy for stream consumers, but other items, including fruits, flowers, and terrestrial insects are also important (Dudgeon, 2008; França *et al.*, 2009). Invertebrate shredders play an important role in organic matter processing, but there are many reports of a paucity or lack of insect shredders in tropical streams in Africa, Asia and Central America (Dudgeon, 1994; Irons *et al.*, 1994; Dobson *et al.*, 2002). In Asian and Caribbean tropical streams crustaceans (especially crabs and shrimps) have been shown to play an important role in breakdown of litter, whereas elsewhere in the tropics leaf litter breakdown by microorganisms has been found to be fast in the absence of shredders (e.g., in Malaysian peat swamps, Encalada *et al.*, 2010).

Benthic invertebrates make up an essential component of all stream food webs and ecosystems. They ingest allochthonous and autochthonous material, and assimilate some of it into body tissue, which in turn is eaten by animals at higher tropic levels (Fisher and Likens, 1973; Turcotte and Harper, 1982; McQueen, 1990). Both the diversity and density of benthic invertebrate communities can be influenced by a number of factors operating at various spatial scales. At a regional scale; climatic conditions, geology and morphology may be important, whereas at small spatial scales, local physico-chemical conditions and biological interactions may override regional controls (Hynes, 1974; Cummins, 1975; Anadu and Akpan, 1986; Galicka *et al.*, 1992).

Increasingly, stream benthic invertebrates have been used as indicators of ecosystem conditions, for example, to assess pollution levels and ecosystem health (Dudgeon *et al.*, 2006; Corbi *et al.*, 2012). Benthic invertebrates can also be good indicators of both large and subtle changes in the quality of freshwater systems (Gibbons and Funk, 1982; Crown *et al.*,

1995; Ajao and Fagade, 2002). This is because they respond to changes more rapidly than larger more mobile aquatic organisms such as fish (Gibbons and Funk, 1982). In some regions, particularly in the tropics some benthic invertebrates also transmit diseases or serve as intermediate hosts for significant human and animal parasites (e.g., malaria fever is transmitted by mosquitoes, onchocerciasis by *Simulium* and schistosomiasis by snails).

Relatively few studies of stream invertebrate life histories and production have been conducted in tropical streams (some in Puerto Rico, e.g., Greathouse and Pringle, 2006), and in most tropical regions there are significant impediments to species or genus level identifications due to a lack of taxonomic studies (Holloway and Barlow, 1983; Dudgeon, 2008). At the ordinal and family level the benthic invertebrate fauna of tropical streams is quite similar to that of northern temperate streams (Hynes, 1970), however, identifying tropical taxa to genus or species is significantly more challenging. In some areas (e.g., Australia, Costa Rica and Hong Kong) taxonomy is relatively advanced, but in others (e.g., West Africa and Nigeria), few species have been formally described, and taxonomic keys and guides are rare (Bixby *et al.*, 2009; Pearson and Boyero, 2009; Solomon *et al.*, 2009).

Climate and vegetation zones of Africa

Africa is the world's second-largest and second-most-populous continent with approximately one billion people (UN, 2009). At about 30.2 million km² including adjacent islands, it covers six percent of the Earth's total surface area and 20.4 percent of the total land area. The Afrotropic ecozone is one of eight global ecozones (Sayre, 1999), it includes Africa south of the Sahara Desert, the southern and eastern fringes of the Arabian Peninsula, the island of Madagascar, southern Iran, extreme south-western Pakistan and the islands of the western Indian Ocean. Most of the Afrotropic region, with the exception of Africa's southern tip, has a tropical climate. A broad belt of deserts, including the Atlantic and Sahara deserts of northern Africa and the Arabian Desert of the Arabian Peninsula, separate the Afrotropic from the Palaearctic ecozones, which includes northern Africa and temperate Eurasia. South of the Sahara, two belts of tropical grassland and savannah run east and west across the continent, from the Atlantic Ocean to the Ethiopian Highlands (Fig. 1).

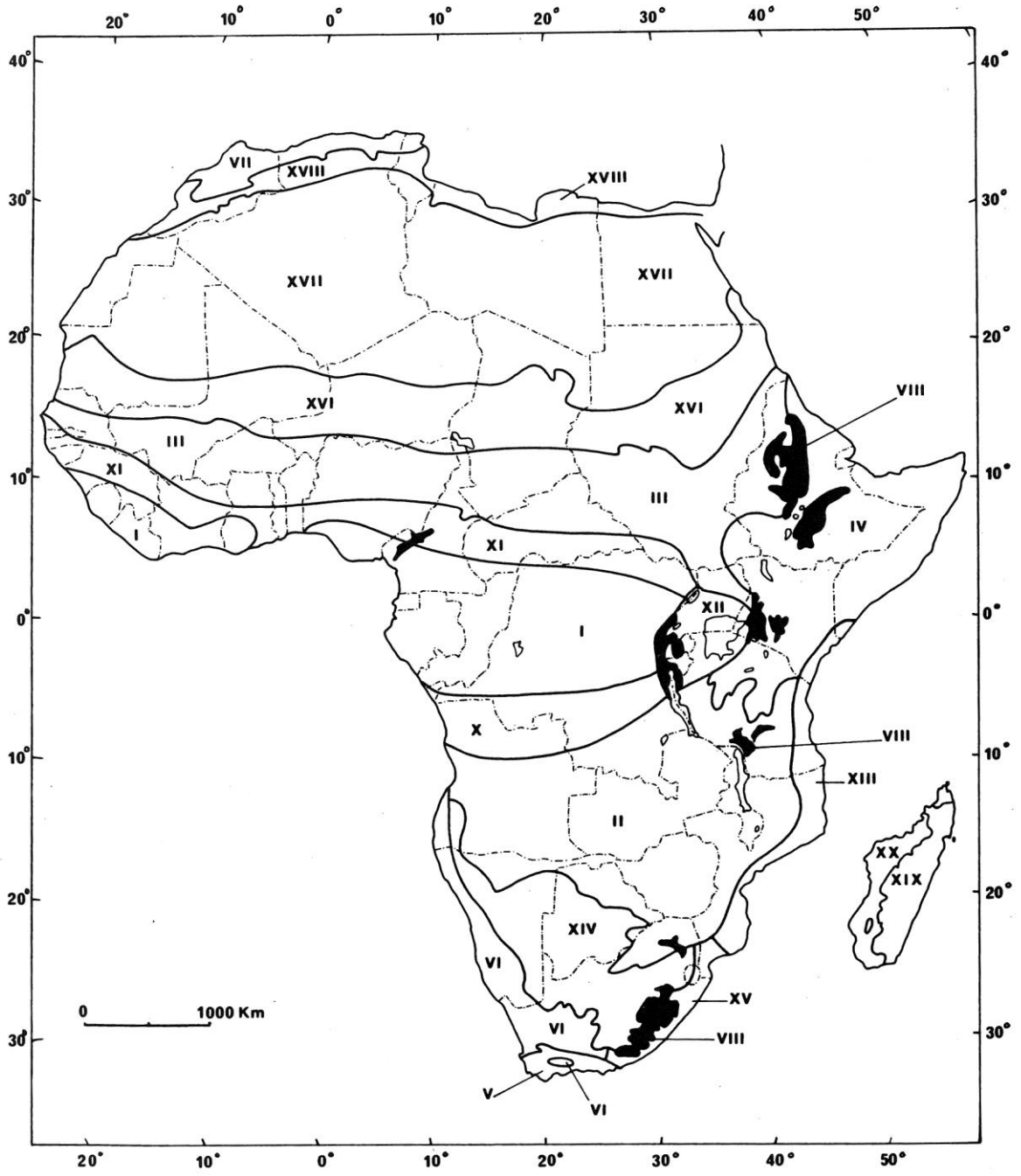

Figure 1: Vegetation of Africa and Madagascar (White, 1983). (I) Guinea-Congolian regional centre of endemism, (II) Zambian regional centre of endemism, (III) Sudanian regional centre of endemism, (IV) Somalia-Masai regional centre of endemism, (VII) Mediterranean regional centre of endemism, (VIII) Afro-montane archipelago-like regional centre of endemism, (X) Guinea/Zambia-inhambane regional mosaic, (XII) Lake Victoria regional mosaic,(XVI) Sahel regional transition zone, (XVII) Sahara regional transition zone,(XVIII) Mediterranean/Sahara regional transition zone, (XIX) East Malagasy regional centre of endemism and (XX) West Malagasy regional centre of endemism.

Immediately south of the Sahara lies the Sahel belt, a transitional zone of semi-arid short grassland and *Acacia* savannah. Rainfall increases further south in the Sudanian Savannah (i.e., the Sudan), a belt of taller grasslands and savannas. The Sudanian Savannah is home to two great flooded grasslands, the Sudd wetland in the Sudan and the Niger Inland Delta in Mali. The forest-savannah mosaic is a transitional zone between the grasslands and the belt of tropical moist broadleaf forests near the equator. The forest zone, a belt of lowland tropical moist broadleaf forests, runs across most of equatorial Africa's intertropical convergence zone. The Upper Guinean forests of West Africa extend along the coast from Guinea to Togo. The Dahomey Gap, a zone of forest-savannah mosaic that reaches to the coast, separates the Upper Guinean forests from the Lower Guinean forests, which extend along the Gulf of Guinea from eastern Benin through Cameroon and Gabon to the western Democratic Republic of the Congo. The largest tropical forest zone in Africa comprises the Congolian forests of the Congo Basin in Central Africa. A belt of tropical moist broadleaf forest also runs along the Indian Ocean coast, from southern Somalia to South Africa (Sayre, 1999).

Tropical latitudes receive heavy seasonal rainfall because of the Hadley circulation (tropical atmospheric circulation), which is caused by the migratory winds at the inter-tropical convergence zone (ITCZ), where northeast trade winds come together (Dudgeon, 2008). Movement of the ITCZ drastically affects rainfall in many equatorial nations, resulting in wet and dry seasons rather than the cold and warm seasons that prevail at higher latitudes. Long term changes in the ITCZ can result in severe droughts or flooding (Djurić, 1994). Thus, tropical streams and rivers are typified by severe hydrological seasonality, although this is to a large extent predictable on the basis of latitude (Dudgeon, 2008).

Since the 1980s, more and more studies have focused on factors influencing biodiversity in the tropics and Africa (Vörösmarty *et al.*, 2010), and these have provided evidence that the taxonomic richness of an area is determined by large scale factors (Ricklefs, 1993; Vinson and Hawkins, 1998; Brosse *et al.*, 2008). Increasing interest has been given to Mediterranean ecosystems of North Africa that have been considered to be biodiversity hotspots (Lavorel and Richardson, 1999; Myers *et al.*, 2000). Similarly the Afrotropical region has been recognized for its high biodiversity. For example it supports numerous endemic bird families, including ostriches (Struthionidae), sunbirds (Nectariniidae), secretary birds (Sagittariidae), guinea fowl (Numididae) and mouse birds (Coliidae). Also, several families of passerines are limited to the Afro-tropics, and include rock-jumpers (Chaetopidae) and rock fowl (Picathartidae). Africa has three endemic orders of mammals, the Tubulidentata (aardvarks), Afrosoricida (tenrecs and golden moles) and Macroscelidea

(elephant shrews). Furthermore, the East-African plains are well known for their diversity of large mammals including those unique to Africa (e.g., African buffalo). Four species of Great Apes (Hominidae) are endemic to Africa: both species of gorilla (western gorilla, *Gorilla gorilla*, and eastern gorilla, *Gorilla beringei*) and both species of chimpanzee (common chimpanzee, *Pan troglodytes*, and bonobo, *Pan paniscus*). Humans and their ancestors originated in Africa (Moritz and Linsenmair, 2001).

Africa also has a strongly freshwater-associated mammal, the hippopotamus, and large aquatic reptiles in the crocodiles and alligators. Some African freshwaters are recognized as systems of high endemism, notably the East African Great lakes (Victoria, Malawi, and Tanganyika), which are well known for their high diversity of freshwater fishes, especially cichlids. They support more than two-thirds of the estimated 2,000 species of Cichlidae, worldwide (Farias, 2000). The central African river fauna comprises 194 fish species, with 119 endemics and only 33 restricted to small areas (Farias, 2000). West African coastal rivers also support 322 known freshwater fish species, 247 restricted to small areas and 129 endemic.

Nigeria lies within the region of West Africa and ranges from the Sahara (to the north), the Gulf of Guinea (to the south), and the Chad basin in the east. The south-eastern limit is the Cross River on the Nigerian-Cameroun border. Tropical West Africa covers an area of approximately 3 million km^2 and has a distinct climatic gradient from north to south.

Freshwater ecology in West Africa and Nigeria

Information on West African river systems is limited, often qualitative or descriptive, although there are a few quantitative studies in research papers, obscure reports and unpublished theses (Leveque *et al.*, 1991). Research on West African rivers has been primarily focussed on making taxonomic inventories, although many species are unknown or still to be described (Leveque *et al.*, 1991).

A number of studies have considered aspects of water quality and the aquatic fauna associated with lakes and impoundments in Nigeria. For example Egborge (1979) and Adesalu (2010) monitored water chemistry of the new lake formed by the impoundment of the River Oshun which formed Lake Asejire, in 1970. In 2010, Adesalu investigated the phytoplankton of the River Oli in Kainji Lake National Park, north central Nigeria and recorded 55 taxa belonging to four major divisions of algae; Bacillariophyta, Chlorophyta, Euglenophyta and Cyanophyta. Taxonomic richness was greatest for green algae but the phytoplankton was not particularly abundant and dominated qualitatively by euglenoids in

particular *Euglena acus*. Adesalu (2010) suggested the relative paucity of phytoplankton in the River Oli may have been partly due to poor light penetration into highly turbid waters.

A study of the benthic invertebrates of the fourth order Ikpoba River in Southern Nigeria was carried out to assess the ecological impact of its impoundment (Ogbeibu and Oribhabor, 2002). The total number of benthic macroinvertebrate taxa and their overall density were significantly higher at upstream control sites than within the impoundment and downstream. Densities of the three most abundant taxonomic groups, Diptera, Oligochaeta and Ephemeroptera differed significantly along the river with Chironomidae (Diptera) dominating the upstream and downstream sites, and Oligochaeta being dominant in the reservoir. The density of Ephemeroptera was significantly reduced within the reservoir and downstream.

In a similar study, Edward and Ugunba (2011) surveyed the macroinvertebrate fauna of Egbe Reservoir, Ekiti State, Nigeria from September 2004 to December 2006. They identified only 18 invertebrate taxa, of which gastropods were the most abundant (41.8 %) and diverse, and Odonata and Ephemeroptera had the lowest diversity and numerical abundance (0.4% and 6.3%, respectively). The gastropod *Melanoides tuberculatus*, which is often cited as an indicator of polluted water, dominated the fauna suggesting that the reservoir was becoming organically enriched (Edward and Ugwumba, 2011).

Several studies have also looked at benthic invertebrate communities in specific Nigerian rivers (Egborge, 1979; Kinako, 1979; Grove, 1985; Ogbeibu and Egborge, 1995; Adesalu 2010; Omoigberale and Ogbeibu, 2010). In one study the diversity and seasonal variation of communities in the Okhuo River in a tropical forest near Benin City was investigated. In that study 86% of the community were arthropods, 9% were annelids (mostly the oligochaetes, *Tubifex* and *Nais* and a few leeches (*Hirudo*)), and 5% were gastropods. Of the arthropods, 75% were insects, mainly Hemiptera and Diptera (Eyo and Ekwonye, 1995). Increasingly, studies in Nigeria have focussed on anthropogenic issues, such as the effects of domestic waste, sewage and heavy metals on river ecology (Odo, 2007). For example, Anadu and Ejike (1981) surveyed the distribution of some fish and the macroinvertebrate fauna of the Dilimi River in relation to open cast mine washings on the Jos Plateau. Macroinvertebrates were absent immediately below mine washing discharge (Anadu and Ejike, 1981).

According to Ogbogu (2013), most studies on West African freshwater ecosystems have been on the systematics of freshwater organisms. Studies on ecosystem dynamics have been lacking due to challenges. Common among these challenges are lack of infrastructure

and analytical equipment, research grants and poor funding for faculties in research institutions, inadequate freshwater science training, non-utilization of research results and political issues. Ogbogu (2013) suggested that improvement in the quantity and quality of freshwater science in the region should start by eliminating or reducing the impact of these challenges. This has become imperative if global climate change and its impacts on West African freshwater ecosystems are to be fully understood and managed (Ogbogu, 2013).

In general it can be concluded that there are few published studies on Nigerian streams compared to some other parts of Africa, i.e., Kenya and South Africa. In Nigeria there is more information on the aquatic ecology of the southern region of the country than the northern region, however, there is no published information on aquatic ecology in the eastern corner of the country where Mambilla Plateau lies.

Mambilla Plateau and the study streams

My study was conducted in the tropical montane region of the Mambilla Plateau, in the south east corner of Taraba State, north eastern Nigeria between longitude 11° 00" and 6° 30" E, and latitude 6° 30" and 7° 15" N (Fig. 2). All sites were in head-water tributaries of the Donga River which flows south west of the Plateau and joins the Benue River before entering the Atlantic Ocean in the Niger Delta. The Plateau is at an altitude of approximately 1500 m a.s.l. The climatic conditions and vegetation associated with this high elevation in Nigeria have been described by Hall and Medler (1975), and Backeus (1992). There are two main seasons, the rainy season and the dry season. The rainy season lasts from late March to the end of October and averages about 250 days, whereas the dry season lasts from November to mid-March (Hall and Medler, 1975; Backeus, 1992). Mean annual rainfall on the Plateau is 1600–2000 mm most of which falls between June and September. The mean monthly minimum air temperature is 15.5–18.5°C and the maximum is 27.5–30.5°C with temperature further decreasing with increasing altitude (Hall, 1975).

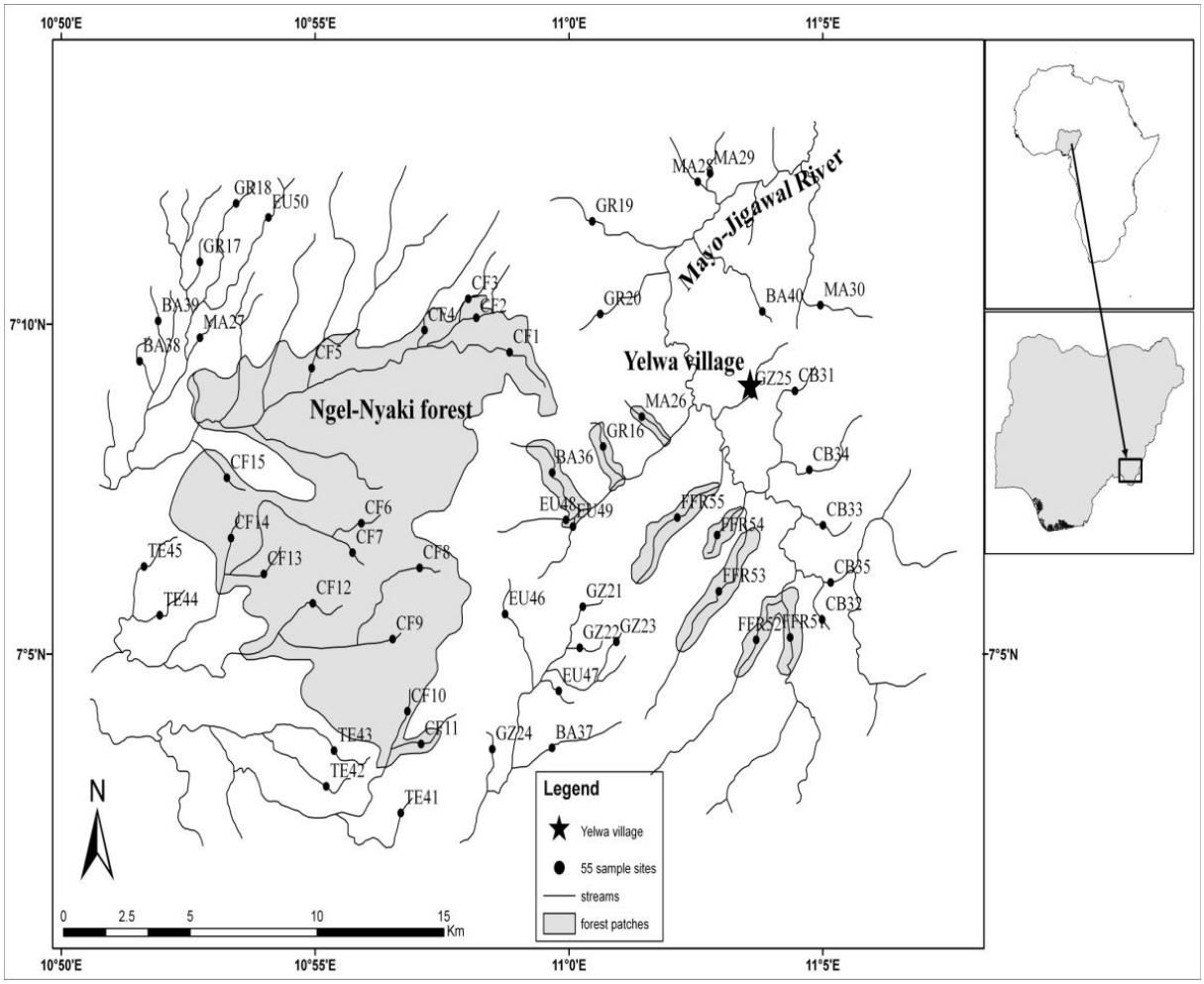

Figure 2: Location of Mambilla Plateau and the 55 study streams, in the south east corner of Taraba State, north eastern Nigeria. (Site codes and names are provided in full in Appendix 2).

The higher elevations of the Mambilla Plateau are dominated by open grass-lands, although fragments of montane forest occur and patches of riparian forest are also common in grassland catchments. Forest vegetation is dominated by *Syzygium guineense, Deinbollia pinnata, Santiria trimera, Rafania* sp., *Croton macrostachyus, Anthonotha noldeae* and *Ficus* spp., whereas in intensive grazing and pastures land occasional pioneer trees such as *Acacia senegalensis, Polyscius fulva, Beeilschmedia* sp., *Pouteria altissima, Bridelia speciosa* occur (Ihuma *et al*., 2011).

My study sites were associated with the Ngel Nyaki montane rainforest. The Ngel Nyaki Forest Reserve covers approximately 46 km² and can be reached on foot from Yelwa village by crossing the Mayo Jigawal River. Altitude within the forest ranges from 1,400 to

1,600 m. Ngel Nyaki was formally gazetted a local authority Forest Reserve under Gashaka - Mambilla Native Authority Forest order of April 1969, but at present it is under the management of the Taraba State Government and the Nigerian Conservation Foundation (NCF), with the Nigerian Montane Forest Project (NMFP) as a project partner (Ihuma *et al.*, 2011). The Ngel Nyaki Forest Reserve includes several third order streams and tens of second order streams.

Vegetation cover and land use on the Plateau includes tropical montane forest, riparian forest, riparian forest fragments and intensive cropping (Fig. 3). I selected streams flowing through a range of intensive land uses typical of the Plateau including maize, tea, cabbage, *Eucalyptus* plantation, banana plantation, grassland and cattle grazing land (Fig. 4).

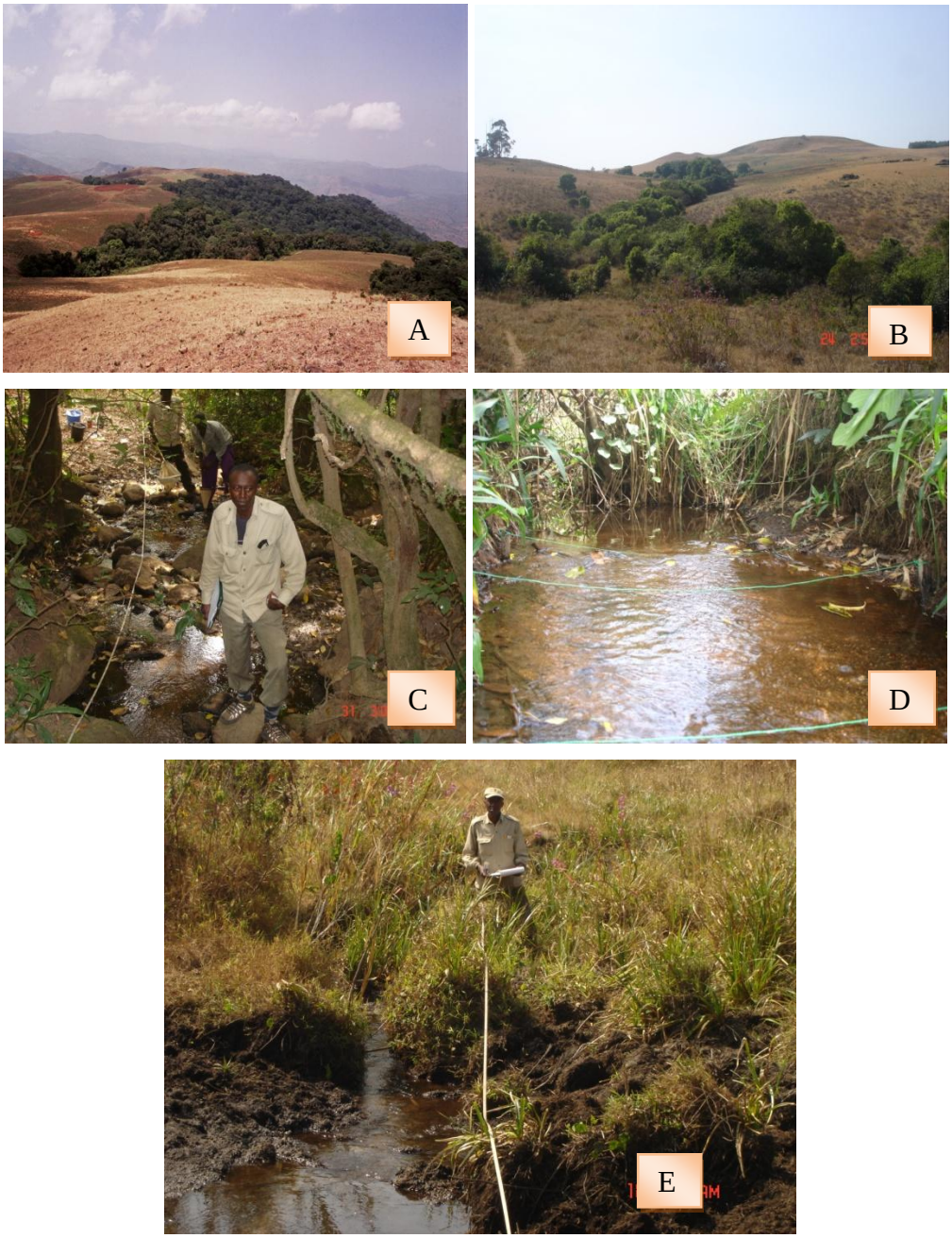

Figure 3: (A) The montane forest of Ngel Nyaki Forest Reserve (B) Riparian forest fragments are common along streams in grassland catchments surrounding the Ngel Nyaki forest (C) forested stream beds are dominated by boulders and cobble substrates, whereas (D) sandy substrate and (E) soft mud substrate are common in open pasture streams on the Mambilla Plateau.

Figure 4: Streams affected by a range of land uses occur on the Plateau and including (A) maize (B) tea, (C) cabbage, (D) *Eucalyptus* plantation, (E) banana plantation and (F) grassland with livestock grazing (mainly cattle).

Aims of the thesis

The primary aim of my research was to investigate how land use affects stream benthic communities in highland tropical streams in Nigeria. However, the stream invertebrate fauna of these streams was completely unknown at the start of my study so to undertake the work I needed to invest considerable time in sampling and identification of the fauna. During the study, an extensive field survey and a series of experiments were conducted in the field between October 2009 and February 2012.

The main data chapters (3, 4 & 5) of the thesis are written as stand-alone manuscripts that I hope will be submitted for publication. As a result, some of the chapters share introductory materials or figures. Acknowledgements of the contributions of others are made as appropriate in the chapters.

Chapter one is this "General introduction", which has provided a broad introduction to the benthic ecology of tropical streams, briefly reviews the current literature on Nigerian streams and highlights some land use issues relevant to tropical systems.

As there are no keys or guides to the aquatic invertebrate fauna of West Africa, therefore, I developed Chapter two as "An illustrated guide to freshwater invertebrates of the Mambilla Plateau Nigeria".

Chapter three investigates the response of benthic invertebrate diversity and communities to a gradient of land use. I surveyed 55 streams ranging from pristine forest to intensive cropping in order to improve our understanding of how tropical stream ecosystems change in response to land use. I see such understanding as a major priority for better management and conservation of Nigerian streams and rivers.

Chapter four is focussed on the importance of riparian land use and in stream leaf litter decomposition. Leaf litter decomposition experiments were carried out in nine selected streams; three in forest, three in maize and three in tea plantations between 2010 and 2011 to determine the rate of decomposition of organic matter, and describe an ecosystem processes in streams across the contrasting land uses.

Chapter five investigates the structure of stream food webs in the same nine streams used in chapter four. Understanding the fate of energy and nutrients and the nature of the complex interactions among producers and consumers is a fundamental theme in ecology (Cohen *et al.*, 1986; Pimm and Kitching, 1987; Polis, 1994). However, this knowledge is also an essential pre-requisite for the sustainable management of aquatic and terrestrial ecosystems, because many human activities affect food web structure and hence important ecosystem process (Douglas *et al.*, 2005).

The final chapter (six) is a general discussion. In it I summarize the results and conclusions of my previous chapters, highlight insights obtained in understanding stream community dynamics on the Mambilla Plateau, and discuss the potential generality of a highland model of stream benthic communities. Finally, I discuss the issues facing the management of streams on the Mambilla Plateau.

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Chapter two

Illustrated guide to freshwater invertebrates of the Mambilla Plateau, Nigeria

Introduction

In Nigeria, apart from a review of the diversity of aquatic faunal resources (Egborges, 1993), studies on the ecology of stream benthic invertebrate communities are limited. Faunistic works include keys for the identification of tropical freshwater fauna by Miles and Graham (1970), a checklist of macroinvertebrates of the Ikpoba River (Ogbeibu and Oribhabor, 2002), and a study of macroinvertebrate fauna from pools in the flood plain of the Anambra River (Eyo and Ekwonye, 1995).

Several studies have investigated benthic invertebrate communities in specific rivers; Anambra River (Eyo and Ekwonye, 1995), (Ogbeibu and Egborge, 1995) and Ogba River (Olomukoro and Okologume, 2008). Several studies of the impact of pollution have focussed on domestic waste, sewage and heavy metals on benthic invertebrate communities (Ofojekwu *et al.*, 1996) and Omeozor (1995) described benthic communities influenced by substrate conditions. Variation in the distribution of species as a result of difference in pH, salinity and dissolved oxygen has also been shown by Zabbey and Hart (2005). In most of these studies, invertebrates have been identified to family, and occasionally genus. However, most identification have had to be made using general text and keys that deal largely with European and North American faunas rather than the Nigerian fauna, or even African freshwater invertebrates. Therefore, past identifications should be treated with caution, as a number may be shown to be incorrect when more detailed taxonomic studies have been made of the local fauna. Many aquatic insect larvae have not been associated with adults, and consequently their identification to species is not possible (Boulton *et al.*, 2008; Pearson and Boyero, 2009; Solomon *et al.*, 2009).

In this chapter I present an illustrated guide to the most common benthic stream invertebrates found in tropical highland streams on the Mambilla Plateau in Nigeria. They include Crustacea and insects in the orders Ephemeroptera (mayflies), Plecoptera (stoneflies), Trichoptera (caddisflies), Odonata (dragonflies), Coleoptera (beetles), Hemiptera (bugs) and Diptera (true flies).

Methods

Invertebrates were collected from continuous sub-montane forest, grassland, grazing, eucalyptus plantations and cropping habitats (in the vicinity of Ngel Nyaki Forest Reserve in the tropical montane region of the Mambilla Plateau, in the south east corner of Taraba State, Nigeria (11° - 6° E and 6° - 7° N) (Fig. 1).

Both quantitative and qualitative benthic invertebrates were collected in 55 streams. Quantitative samples were taken using Surber samplers (0.1m², 250 μm mesh net), and in order to get a more extensive qualitative species list, a single composite kick net sample was also taken from a range of the different micro-habitats in each stream. Where they occurred, leaf packs, wood jams and mosses were included in kick-net samples. Samples were preserved in 70% ethanol (Winterbourn *et al.,* 2006), and were later identified in the laboratory using a Nikon SMZ 800 stereo dissecting microscope. Most images included in this chapter were taken by Stephen Moore of Landcare Research, Auckland using an Auto montage system. The montage photos are higher quality, unfortunately Mr Moore died during the course of the study so montage photos are not available for all taxa. Other taxa were captured with a LEICA DFC295 digital camera. As some taxa only occured as single specimens and some were significantly damaged, not all taxa have photos. Identifications were made using a combination of Stehr (1987); Thorp and Covich (1991); Merritt and Cummins (1996); Yule and Yong (2004) and Blakely *et al.* (2010). Comments on the various taxa provided below are based primarily on information given in these volumes. A total of 74 taxa were identified from 10 orders including; 8 mayflies, 1 stoneflies, 10 caddisflies, 5 dragonflies, 10 beetles, 8 dipteran, 10 true bugs, 3 crustaceans, 2 flat worms, 1 round worm and 2 snails taxa (Table 1). Photos and drawings of as many of the taxa as possible have been included. Some brief observations on ecology and habitat are given.

Table 1: Macroinvertebrate taxa identified in this study, photos and drawings of many of the taxa as possible have been included in this guide.

Phylum	Subphylum	Class	Order	Family	Subfamily	Tribe	Genus	Species
Arthropoda		Insecta	Ephemeroptera	Oligoneuriidae			*Elassoneuria*	
				Siphloneuridae				
				Ephemeridae				
				Baetidae			*Baetis*	sp. A
				Baetidae				sp. B
				Leptophlebiidae				Sp. A
				Leptophlebiidae				Sp. B
				Leptophlebiidae				Sp. C
				Leptophlebiidae			*Adenophlebioides*	
				Heptageniidae				
				Caenidae				
				Polymitarcyidae			*Povilla*	
			Plecoptera	Perlidae			*Neoperla*	
				Perlidae				sp. B
			Trichoptera	Hydropsychidae				sp. A
				Hydropsychidae				sp. B
				Hydropsychidae	Hydropsychinae			
				Philopotamidae				
				Polycentropodidae				
				Psychomyiidae				
				Leptoceridae				sp. A
				Leptoceridae				sp. B
				Glossosomatidae				
				Brachycentridae				
				Hydroptilidae			*Bibusa*	
				Philopotamidae				
				Limnephilidae			*Limnephilus*	
Arthropoda		Insecta	Trichoptera	Sericostomatidae				
			Odonata	Gomphidae				
				Aeshnidae				
				Libellulidae				
				Macromiidae				
				Calopterygidae				
			Coleoptera	Dysticidae			*Dytiscus*	

Phylum	Subphylum	Class	Order	Family	Subfamily	Tribe	Genus	Species
				Hydrophilidae			*Deralus*	
				Gyrinidae			*Orectochilus*	
				Chrysomelidae			*Agasicles*	*A. hygrophila*
				Psephenidae				
				Scirtidae				
				Elmidae				sp. A
				Elmidae				sp. B
				Staphylinidae				
				Ptylodactylidae				
			Hemiptera	Belostomatidae			*Belostoma*	
				Naucoridae				
				Nepidae			*Nepa*	
				Nepidae			*Ranatra*	
				Gerridae				
				Veliidae			*Rhagovelia*	
				Veliidae	Veliinae			
				Mesoveliidae				
				Hydrometridae			*Hydrometra*	
				Corixidae		Corixini	*Corixa*	
				Notonectidae				
				Gelastocoridae				
			Diptera	Tipulidae	Tipulinae		*Leptotarsus*	
				Tipulidae	Limoniinae	Hexatomini		
Arthropoda		Insecta	Diptera	Simuliidae			*Simulium*	*S. damnosus*
				Culicidae				
				Chironomidae	Chironominae	Chironomini		sp. A
				Chironomidae	Chironominae	Chironomini	Chironomus	sp. B
				Chironomidae	Tanypodinae	Pentaneurini		
				Ceratopogonidae				
				Syrphidae			*Eristalis*	
				Arthericidae				
				Psychodidae				
	Crustacea		Decapoda	Astacidae			*Astacopsis*	
				Atydae				
			Brachyura	Potamonautidae				
Platyhelminthes			Tricladida					

Phylum	**Subphylum**	**Class**	**Order**	**Family**	**Subfamily**	**Tribe**	**Genus**	**Species**
		(Hirudinea)						
Annelida		Oligochaeta		Naididae				
Mollusca		Gastropoda		Thiaridae			*Melanoides*	*M. tuberculatus*
				Planorbidae			*Bulinus*	*B. globosus*

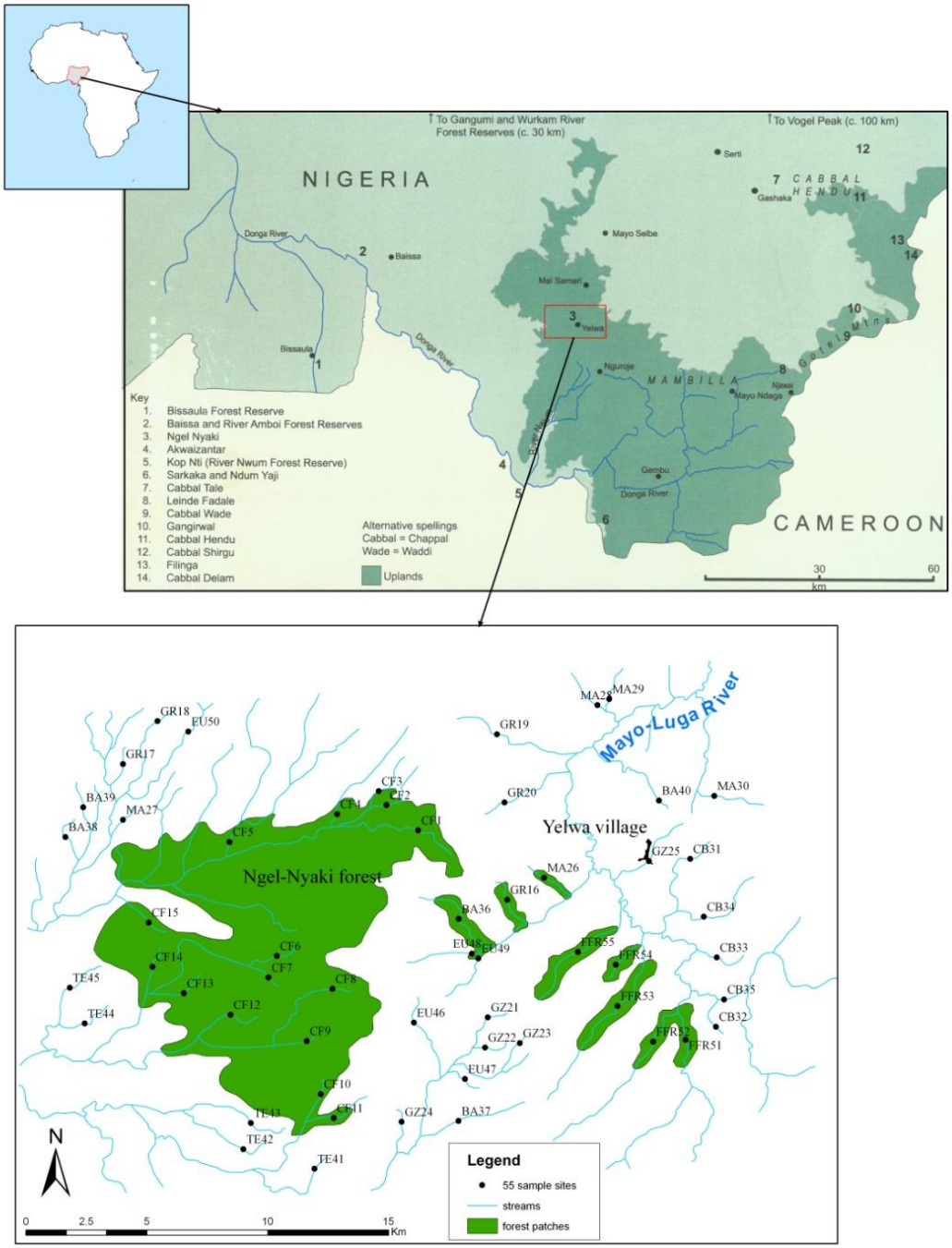

Figure 1: Map of the Mambilla Plateau, north-east Nigeria. Study streams are located near Yelwa village.

What are freshwater invertebrates?

Freshwater benthic invertebrates are small animals (ranging in size from microscopic to many millimetres) which do not have back-bones. They are diverse and include worms, leeches,

crustaceans, insects and snails. This study focus on macroinvertebrates (i.e., >500 µm) which can usually be seen with the naked eye. Benthic invertebrates have many reproductive strategies and life cycles, with some groups (e.g., snails and worms) spending their entire lives in water while others (e.g., insect's larvae or nymphs) spend only part of their life in water and their winged adults live in terrestrial environment. Benthic invertebrates can be abundant in freshwater and can be used as indicators of changes in water quality, they also form an important part of aquatic food webs. Because of their ability to respond to physical (e.g., temperature), chemical (e.g., pH) and habitat (e.g., sediment or substrate size) changes in freshwater conditions, benthic invertebrates are often used for biomonitoring and can provide useful information on natural and anthropogenic disturbance gradients.

Functional Feeding Groups used in this study

Invertebrate species can eat by a number of different methods we term these functional feeding groups (FFG). The relative abundance of invertebrate feeding functional groups can reflect the types of food available in a stream for example a forested stream full of leaves may have invertebrates which are shredders i.e., they shred the leaves. Dominance of, or loss of, a particular group may indicate a change in the ecological status of the waterway. The ideal "healthy" aquatic habitat would have representative of several functional feeding groups (Table 2). The functional feeding groups listed below are adapted from Merritt and Cummins (1996).

Table 2: Feeding functional groups used in this study

FFG	Food
Shredders	Decomposing plant tissue e.g., leaves and wood.
Filter feeders	Suspended fine particulate organic matter (FPOM) e.g., small particles of leaves or algae that are in the water column.
Collector-gatherers	Deposited decomposing fine particulate organic matter (FPOM) e.g., particles in the stream bed.
Scrapers (or grazers)	Biofilm i.e., periphyton, bacteria, fungi.
Predators (scavengers)	Living animals. Scavengers feeding on dead animals are generally rare.
Macrophyte piercers	Living vascular plant and algal fluid.

Taxonomic classifications used in this study

Living organisms are classified into a series of hierarchical groups, based to a large extent on consistent morphological features. In this study the standard international classification scheme has been used as shown below.

Kingdom (e.g., Animalia)

Phylum (e.g., Arthropoda)

Class (e.g., Insecta)

Order (e.g., Diptera)

Family (e.g., Tipulidae)

Subfamily (e.g., Limoniinae)

Tribe (e.g., Hexatomini)

Genus (e.g., *Paralimnophila*)

Species (e.g., *Paralimnophila skusei*)

Key to the aquatic macroinvertebrates of the Mambilla Plateau

This key has been largely adapted from keys in Yule and Yong (2004) and for most groups is taken to family level. Because knowledge of the taxonomy and systematic of the Nigerian freshwater fauna is limited it is not possible to identify a large proportion of the fauna beyond this level with confidence. Many aquatic larvae need to be reared to adults to obtain associations needed for the assignment of larvae to genera and species. Therefore, a conservative approach has been taken to the assignment of names below family level. The key includes all macroinvertebrate groups found during the present study on the Mambilla Plateau.

Key to major groups including insect orders

1 With a calcified shell.....Phylum **Mollusca** (Key D)

\- Without a shell.....2

2 Body not segmented, flat, worm-like.....Phylum **Platyhelminthes**
(unidentified flatworms in the order Tricladida occur in Mambilla Plateau streams)

\- Body segmented; maybe worm-like.....3

3 Without jointed limbs.....4

\- With jointed limbs.....Phylum **Arthropoda**, 5

4 Body soft and worm-like with more than 15 visible segments..Phylum **Annelida** (Key C)

\- Body with fewer than 15 visible segments; sclerotised mouthparts may be visible; some non-jointed prolegs may be present.....**larvae of Diptera and some Coleoptera**

5 With 3 pairs of legs.....Class **Insecta** (Key B)

\- With more than 3 pairs of legs.....**Crustacea** (Key A)
(Other non-insect arthropods such as mites and spiders (Arachnida) were not found in the present study)

Key A. Crustacea

1 Appendages present on all abdominal segments; 5 pairs of walking legs; eyes on stalks; moderate-large animals.....**Decapoda**, 4

- Abdominal appendages present only on last segment; small animals (<5mm).....2

2 With a bivalve carapace enclosing all or most of the animal.....3

- Without an enclosing carapace; body pear-shaped; antennae prominent; a single median eye present.....**Copepoda**

3 Carapace encloses thorax and abdomen but not head; eye and antenna prominent (water fleas).....**Cladocera**

- Carapace encloses the entire animal including the head (seed shrimps).....**Ostracoda**

4 Abdomen small and folded beneath thorax; body rather flattened and rounded; rostrum reduced or absent; tail fan absent (crabs).....**Brachyura**

(A species of Potamonautidae, the largest family of freshwater crabs in Nigeria was found on the Plateau)

- Abdomen large and extended, not folded beneath the thorax; rostrum projecting in front of the eyes; antennae long and prominent.....6

5 Abdomen straight, long and symmetrical; first 3 pairs of walking legs chelate, the first pair forming large pincers (crayfish).....**Astacidea**

(Nigerian freshwater crayfish belong to the family Astacidae. A species of *Astacopsis* was found on the Plateau)

- Abdomen usually angled strongly from its third segment; first 2 pairs of walking legs chelate but not forming powerful pincers (shrimps).....**Caridea**

(Shrimps found on the Plateau belonged to the family Atyidae)

Key B. Insecta

1 Thoracic legs each with a single claw; abdomen with lateral or dorsal gills, which are often lost on collection; three, or sometimes two, caudal filaments ("tails") present (mayflies)..... .....**Ephemeroptera** (Key B1)

- Thoracic legs each with two tarsal claws; two caudal filaments (cerci); no lateral abdominal gills present, although tufts of gills may be present on the thorax (stoneflies).....**Plecoptera**

(A single family Perlidae with one species of *Neoperla* is known from the Mambilla Plateau)

2 With a prominent mask formed by the extensile labium, beneath or in front of the head (dragonflies and damselflies).....**Odonata** (Key B2)

- Without a mask-like labium.....5

3 Abdomen ending in a pair of prolegs that end in a single hook; larvae may have a portable case (caddisflies).....**Trichoptera** (Key B3)

4 Mouthparts in the form of a beak (bugs).....**Hemiptera** (Key B4)

- Mouthparts not in the form of a beak.....4

5 End of the abdomen not exactly as above (beetle larvae).....**Coleoptera** (Key B5)

6 Forewings in the form of hard elytra that cover the hind-wings when at rest and meet in the midline of the insect; mouthparts not a pointed beak (beetles).....**adult Coleoptera** (Key B6)

- Not as above.....2

7 Developing wingpads present dorsally on one or two thoracic segments of more mature larvae.....3

- Developing wingpads never present.....6

With three pairs of segmented legs on the thorax.....7

- Without three pairs of segmented legs on the thorax (flies).....**Diptera** (Key B7)

Key B1. Ephemeroptera (mayflies)

1 Forelegs with conspicuous rows of long setae on femora and tibia.....**Oligoneuriidae**
(The genus on the Plateau appears to be *Elassoneuria*)

- Forelegs without long rows of setae.....2

2 Abdominal gills attached dorsally; legs flattened for burrowing; head with curved mandibular tusks.....**Polymitarcidae**
(The genus *Povilla* has been recorded from Nigeria. If species of Ephemeridae also occur they should key out here)

- Abdominal gills attached laterally; no mandibular tusks.....3

3 Squarish gills of abdominal segment 2 large, overlapping and covering all other gills; no hind-wing pads present.....**Caenidae**

- Gills not as above.....4

4 Head and body strongly flattened; mouthparts not visible dorsally.....**Heptageniidae**
(The genus *Heptagenia* has been reported from Nigeria)

- Body less strongly flattened; outer margins of mandibles visible in dorsal view.....5

5 Gills plate-like; median caudal filament short; hind corners of the posterior abdominal segments not spine-like.....**Baetidae**
(The genera *Baetis* and *Cloeon* are known from Nigeria but their larvae have not been distinguished)

- Gills slender and bifid; all 3 caudal filaments of similar length.....**Leptophlebiidae**
(Some larvae found on the Plateau resemble those of *Adenophlebioides*)

Key B2. Odonata (dragonflies and damselflies)

1 Larvae slender with a narrow abdomen terminating in 2 or 3 gill lamellae (damselflies).....
.....**Zygoptera**
(Larvae of Calopterygidae have been identified on the Plateau)

- Larvae stout with a broad abdomen and no gill lamellae (dragonflies).... **Anisoptera**, 2

2 Antennae 4-segmented; tarsi of 1st and 2nd legs 2-segmented.....**Gomphidae**

- Antennae with 5-7 segments; all tarsi 3-segmented.....3

3 Labial mask flat; body elongate, not flattened.....**Aeshnidae**

- Labial mask spoon-shaped; body short and somewhat flattened.....**Libellulidae** and **Macromiidae**
(The family Macromiidae was considered to be a subfamily of Corduliidae until recently. Macromiid larvae on the Plateau had thin striped legs. At least 6 species of Libellulidae are know from the Plateau but their larvae have not been distinguished)

Key B3. Trichoptera (caddisflies)

1 Middle and hind legs with fringes of long filtering setae; case made from 2 pieces of leaf placed laterally.....**Brachycentridae**

- Legs and case not as above.....2

2 Dorsal surfaces of all 3 thoracic segments with a large sclerotised plate.....3

- Second and third thoracic segments lacking large sclerotised plates.....4

3 Abdominal segments with tufts of latero-ventral gills; posterior proleg terminating in a large brush and hook; larva lives in a fixed retreat.....**Hydropsychidae**
(Several species in the subfamily Hydropsychinae occur on the Plateau)

- Very small caddis with no gills; final stage larvae with a swollen abdomen and a purse-like case; younger larvae with no case.....**Hydroptilidae**
(Larvae of *Bibusa* have been found in Nigeria and can be recognised by the presence of filamentous red algae incorporated into their cases)

4 Larvae with a portable case.....5

- Larvae without a portable case.....6

5 Antennae about 6 times as long as wide; hind trochanters (leg segment 2) about as long as segments 1 (coxa) and 3 (femur), making the hind legs very long; cases of various materials.....**Leptoceridae**

- Antennae short and inconspicuous; hind trochanter short; abdominal segment 9 with a dorsal plate; case turtle-like in appearance, made from sand grains.....**Glossosomatidae**

6 Labrum membranous and T-shaped; larvae live in a silken, stocking-like net..**Philopotamidae**

- Labrum sclerotised and rounded laterally, not T-shaped.....7

7 Prothoracic trochantin (not trochanter) broad and hatchet-shaped; abdomen without a lateral fringe of hairs; larvae live in tubes on stones and logs.....**Psychomyiidae**

- Prothoracic trochantin not hatchet-shaped; abdomen with a lateral fringe of hairs; larvae occupy silken retreats or nets.....**Polycentropodidae**

Key B4. Hemiptera (true bugs)

1 Antennae exposed and longer than head.....2

- Antennae inserted beneath eyes and shorter than head.....4

2 Head very long with eyes about half way along it (water measurers).....**Hydrometridae**

- Head not excessively long; eyes at base of head.....3

3 Head with a median longitudinal groove on dorsal surface; middle femora rarely extending beyond tip of abdomen (small water striders).....**Veliidae**
(A common genus on the Plateau is *Rhagovelia*, which has a plume of hairs on the tarsi of the middle legs)

- Head without a median longitudinal groove on dorsal surface; middle femora extending well beyond tip of abdomen (water striders/pond skaters).....**Gerridae**

4 Tip of abdomen with paired respiratory processes.....5

- Tip of abdomen without paired respiratory processes.....7

5 Respiratory processes strap-like and retractable; body ovoid and flat (giant water bugs).....**Belostomatidae**
(The species found on the Plateau fits descriptions of *Belostoma* from elsewhere)

- Respiratory processes cylindrical, rigid, non-retractile, usually long and narrow; body ovoid or cylindrical.....**Nepidae**, 6

6 Body narrow and cylindrical (needle bugs).....***Ranatra***

- Body broad and flat (water scorpions).....***Nepa***

7 Ocelli present on head; head much wider than long; fore-femora thickened and swollen at some point; littoral dwellers, semi-aquatic (toad bugs).....**Gelastocoridae**

- Ocelli absent.....8

8 Body and forewings with transverse dark lines; rostrum broadly triangular, transversely striate; fore-tarsi scoop-like (water boatmen).....**Corixidae**
(Species found on the Plateau belong to the tribe Corixini)

- Appearance of body not as above; fore-tarsi not scoop-like.....9

9 Forelegs not raptorial; body elongate; hindlegs elongate, oar-shaped; swim ventral side up (backswimmers).....**Notonectidae**

- Forelegs raptorial; body flat; head much wider than long; swim dorsal side up (creeping water bugs).....**Naucoridae**

Key B5. Coleoptera larvae (beetle larvae)

1 Legs very small; thorax and abdomen short, soft and lacking distinct sclerites (plates); last abdominal segment with a pair of ventral hooks (leaf beetles).....**Chrysomelidae**

- Legs with 3-6 segments present; body appearance not as above.....2

2 Legs with 2 claws.....3

- Legs with a single claw.....4

3 Abdomen white, 10-segmented, with elongate spine-like gills on each segment; 2 stout hooks at the tip of the abdomen (whirligig beetles).....**Gyrinidae**

- Abdomen 8-segmented without terminal hooks; lateral gills absent (diving beetles)..... .....**Dytiscidae**

4 Antennae long, muitisegmented (marsh beetles).....**Scirtidae**

- Antennae short, inconspicuous and composed of 2-3 segments.....5

5 Body greatly flattened, round-oval in shape; head and legs not visible from above (water pennies).....**Psephenidae**

- Body shape not as above; head and legs visible from above.....6

6 Abdominal segment 9 with a lid-like operculum covering a chamber from which gills and/or hooks can be protruded; labrum and clypeus not fused together (riffle beetles)..... **Elmidae**

- Abdominal segment 9 without an operculum; anterior margin of fused labro-clypeus variably serrated (water scavenger beetles).....**Hydrophilidae**

Key B6. Coleoptera adults (beetles)

1 Aquatic plant dwelling beetle with prominent yellow and black striped elytra (wing covers) (alligator weed beetle).....**Chrysomelidae**
(The leaf beetle found on the Plateau is the introduced alligator weed beetle *Agasicles hygrophila*)

- Not yellow and black striped.....2

2 Body elongate with very short elytra that cover little or any of the abdomen; beaded antennae longer than the head; living close to water but not usually fully aquatic (rove beetles).....**Staphylinidae**

- Not as above; fully aquatic beetles.....3

3 Head with two pairs of dorsal and ventral eyes; forelegs much longer than the oar-like middle and hind legs (whirligig beetles).....**Gyrinidae**
(More than one genus occurs on the Plateau, including the large *Orectochilus*, which has a tufted brush on the naxilla)

- Head with one pair of eyes; all legs of similar length.....4

4 Metasternum with lateral “wings”; coxae of hind legs very large (diving beetles).....**Dytiscidae**
(Several genera and species of a range of sizes occur on the Plateau. They include the large *Dytiscus*)
- Metasternum without wings; coxae of hind legs not excessively large.....5
5 Base of each antenna beneath the head so the entire antenna not visible from above (the visible appendages are maxillary palps); the 3 distal antennal segments form a club; abdomen with 4-5 visible sternites (water scavenger beetles).....**Hydrophilidae**
(One genus identified on the Plateau is *Deralus*)
- Base of each antenna visible from above; all antennal segments similar, bead-like (riffle beetles).....**Elmidae**

Key B7. Diptera (two-winged flies)

1 Head capsule more or less complete; biting mouthparts move horizontally.....2
- Head capsule variously reduced often to rods with associated hooks that move in a vertical plane.....3
2 Head capsule can be retracted into thorax; tip of abdomen with a lobed respiratory disk with 2 spiracles (craneflies).....**Tipulidae**
(Larvae found in Plateau streams belong to the subfamilies Tipulinae (possibly genus *Leptotarsus*) and Limoniinae, which is considered to be a family by some authorities)
- Not as above.....3
3 Prolegs present.....4
- Prolegs absent.....5
4 With a single prothoracic leg; abdomen swollen; head with labral fans and mouth brushes (black flies).....**Simuliidae**
(The genus found in Nigeria is *Simulium*)
- Pairs of prolegs on the first thoracic and last abdominal segments; body narrow and elongated (non-biting midges).....**Chironomidae**
(Members of the subfamilies Chironominae (genus *Chironomus*) and Tanypodinae (tribe Pentaneurini) have been found on the plateau)
5 Larvae very narrow with a bullet-like head; body segments usually at least twice as long as wide; abdomen tip with a thin tuft of hairs (biting midges).....**Ceratopogonidae**

- Not as above.....6

6 Larvae elongate with a rounded head; dorsal surface with numerous transverse hardened plates and/or fringes of hairs along the sides; dark in colour (moth flies).....**Psychodidae**

- Thorax rounded and broader than the abdomen; end of abdomen with a respiratory siphon; head with mouth brushes (mosquitoes).....**Culicidae**

7 Anterior end of body tapering; first 7 abdominal segments with distinct ventral prolegs: tip of abdomen with 3 feathery "tails (watersnipe flies).....**Athericidae**

- Anterior end of body broad and blunt; abdominal prolegs short; tip of abdomen terminating in a long, retractable breathing tube (rat-tail maggots).....**Syrphidae**

Key C. Annelida (segmented worms)

1 Elongate worms with groups of microscopic chaetae on most segments.....**Oligochaeta**

- Extenile annelids with 34 segments subdivided by annulations (rings), a posterior sucker and an anterior sucker surrounding the mouth (leeches).....**Hirudinea**

Key D. Mollusca: Gastropoda (snails)

1 With a tall, conical, yellow-brown shell ornamented with fine ridges; aperture on right hand side when viewed with shell apex uppermost.....***Melanoides tuberculatus*** **(Thiaridae)**

- Pale, globular shell with a short compact spire; aperture on the left hand side when viewed with the apex uppermost.....***Bulinus globosus*** **(Planorbidae)**

GENERALISED AQUATIC INSECT DIAGRAM

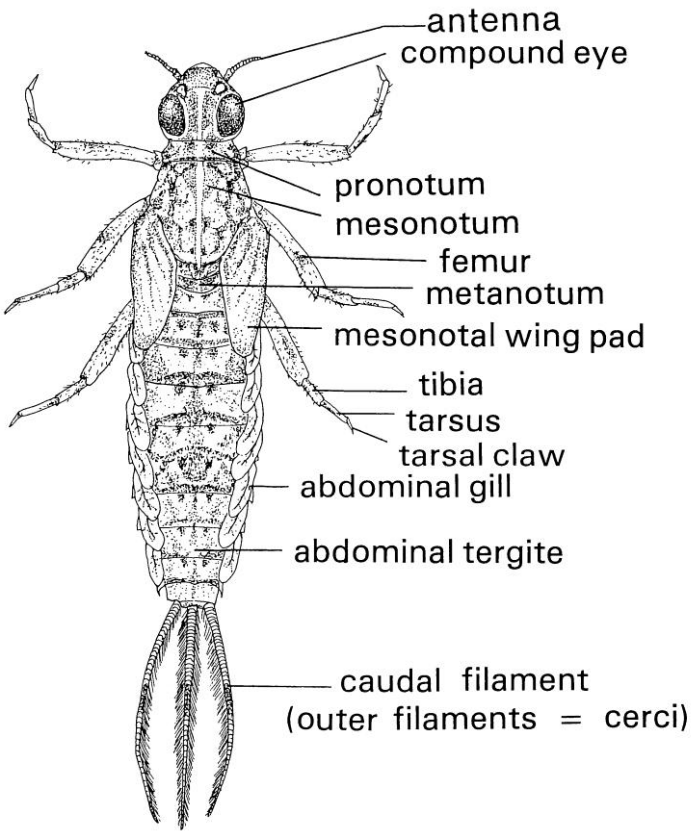

Figure 2: Mayfly larvae (Dorsal view). From Winterbourn *et al*. (2006).

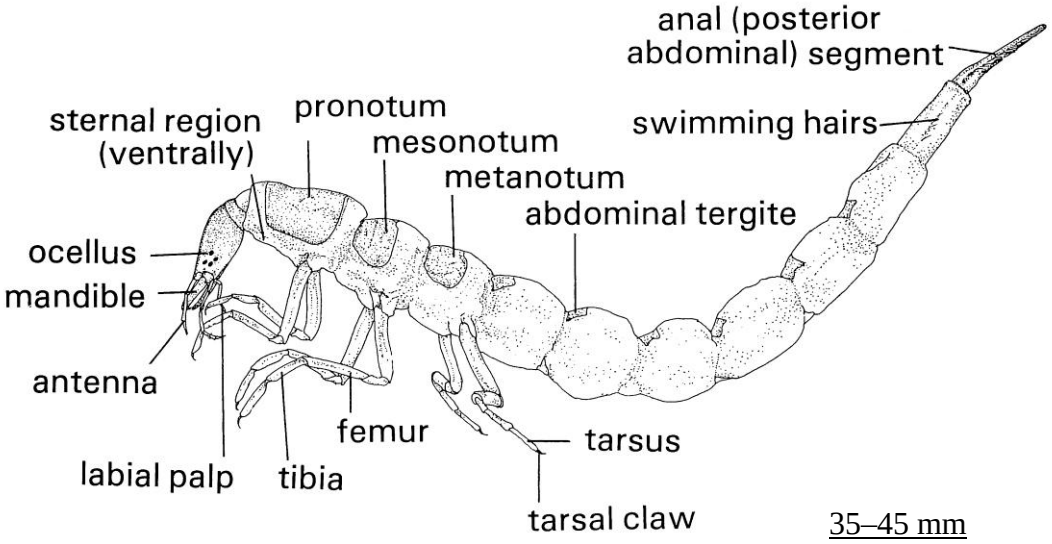

Figure 3: Beetle larvae (Lateral view). From Winterbourn *et al.* (2006).

Phylum: Arthropoda
Class: Insecta

Order: **Ephemeroptera** (mayflies)

Mayflies are hemimetabolous insects meaning that they do not have pupa in their life cycle. In older nymphs wing pads can be seen developing dorsally on the thorax. Mayflies have three "tails" or cerci (occasionally two) and dorsal or lateral gills on most abdominal segments. Each leg has a single tarsal claw (Fig. 4). Adult mayflies live for a few days or even hours. They tend to appear in large swarms. Mayflies spend most of their live as nymph, which may live for years or only a few weeks. They then shed their skin (exuviae) on the water surface and become a flying subadult (subimago), which transforms into an adult (imago) within a day, adults then mate and lay eggs in water. The adults do not feed. At least eight families of Ephemeroptera have been found on the Mambilla Plateau.

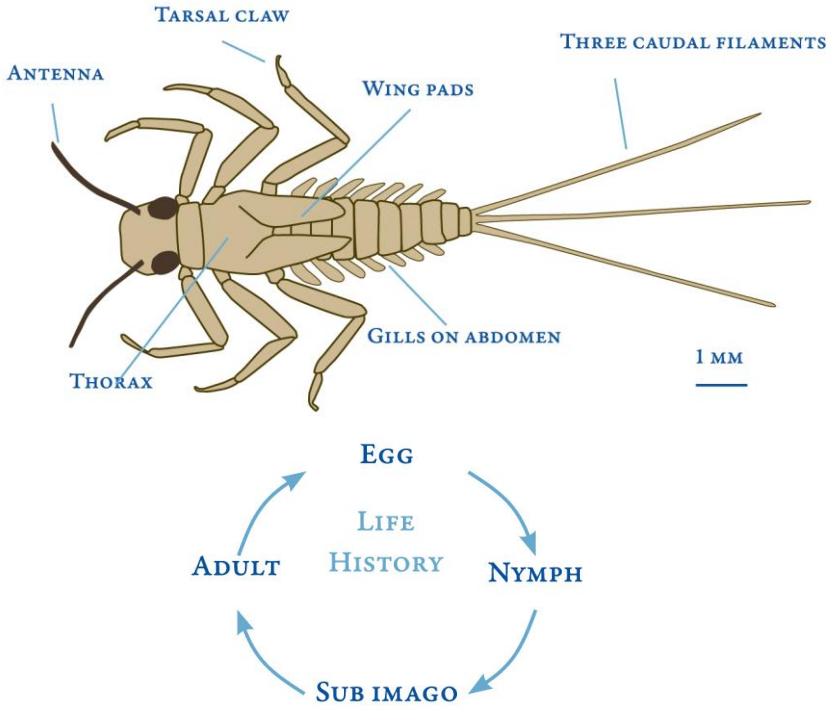

Figure 4: A generalised mayfly and life history.

Family: Oligoneuriidae

A single species which probably belongs to the genus *Elassoneuria* Eaton 1881 (Gillies, 1974) is common in some Mambilla streams. A species of this genus (*E. candida*) was described from Nigeria by Eaton in 1913. It has a streamlined, fish-like, nymph with a body

length of up to 20 mm. This mayfly has a variety of gills, including leaf-like structures on abdominal segments and a prominent tuft of maxillary gills beneath the head and thoracic gills are also present (Fig. 5). Initially it looks like a small fish as it darts around the stream.

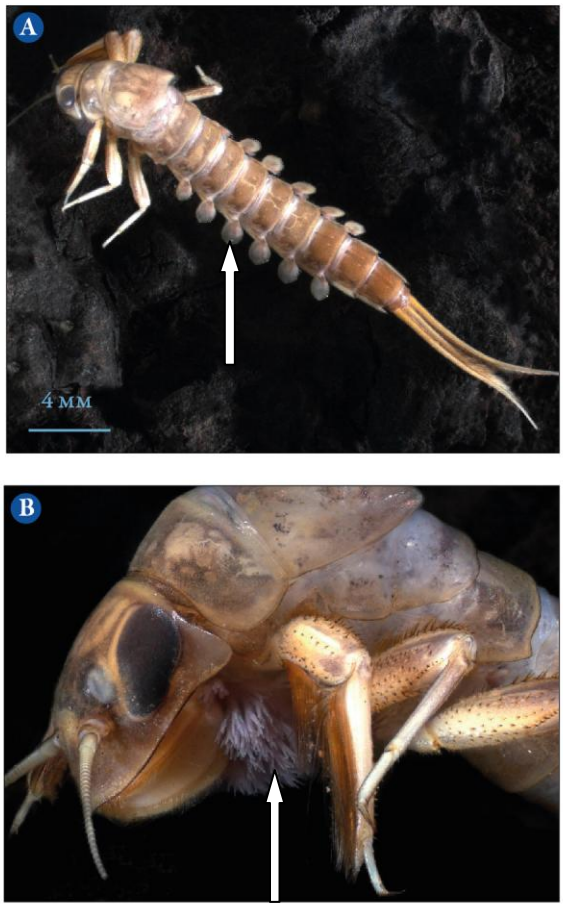

Figure 5: (A) Oligoneuriidae: *Elassoneuria*, with leaf-like abdominal gills and (B) maxillary gills beneath the head. This mayfly can be up to 15 mm long.

Ecological notes: This species can be abundant in forested streams or those with very good water quality. Nymphs are believed to be filter feeders that trap particles with a double row of long setae on the forelegs. Nymphs can have a phoretic association with *Simulium* (Gillies, 2009).

Family: Baetidae

Baetidae have small, fish-like nymphs with a cylindrical to flat body. The head is often small and rounded. Gills are leaf-like, never pronged or feather-like and rarely overlapping. The length of their antennae is about twice the width of the head. The posterior lateral corners of the posterior abdominal segments are rounded and have no sharp points. “Tails” sometimes

have a brush of fine hairs. Some baetids have only two tails or a reduced middle tail that is difficult to see. Several genera of Baetidae are known from Nigeria, including *Baetis* and *Cloeon* but their nymphs have not been distinguished (Fig. 6). These are generally very small mayflies less than 10 mm long.

Figure 6: (A & B) Baetidae larvae, dorsal view.

Ecological notes: Nymphs are fast swimmers. The contents of their gut are primarily algae, and they like to cling to vegetation in the stream. Baetids were found in the continuous forest and forest fragment streams and seem to prefer larger cobble substrate.

Family: Heptageniidae

Nymphs are strongly flattened with large plate-like gills. The head is wide and crescent shaped. When viewed from above the mandibles are hidden beneath the flattened head. There are two slender tail filaments (though they are easily broken). Nymphs usually attach closely to stream substrate and can swim awkwardly; body length up to 20 mm **(**Fig. 7).

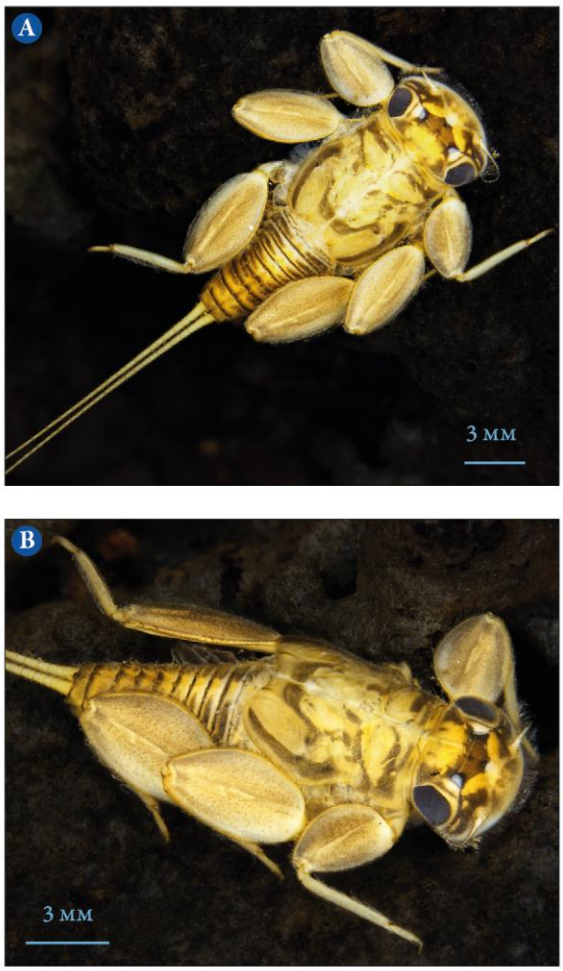

Figure 7: (A & B) Heptageniidae nymphs.

Ecological notes: Heptageniidae can be common in high quality streams, and were found mostly in the forest and forest fragment streams on the Mambilla Plateau. The genus *Heptagenia* has been reported from the Opa River catchment basin, Nigeria (Ogbogu and Oyewole, 2007).

Family: Caenidae

Caenids are commonly known as small, square gill mayflies. Their gills are not found in rows along the sides of the abdomen as in most mayfly nymphs, but hidden beneath a pair of covering flaps (opercula) on abdominal segment 2. The flaps are not fused in the midline but overlap slightly so they look rather like a skirt (Fig. 8**),** these are very small mayflies, generally less than 10 mm long.

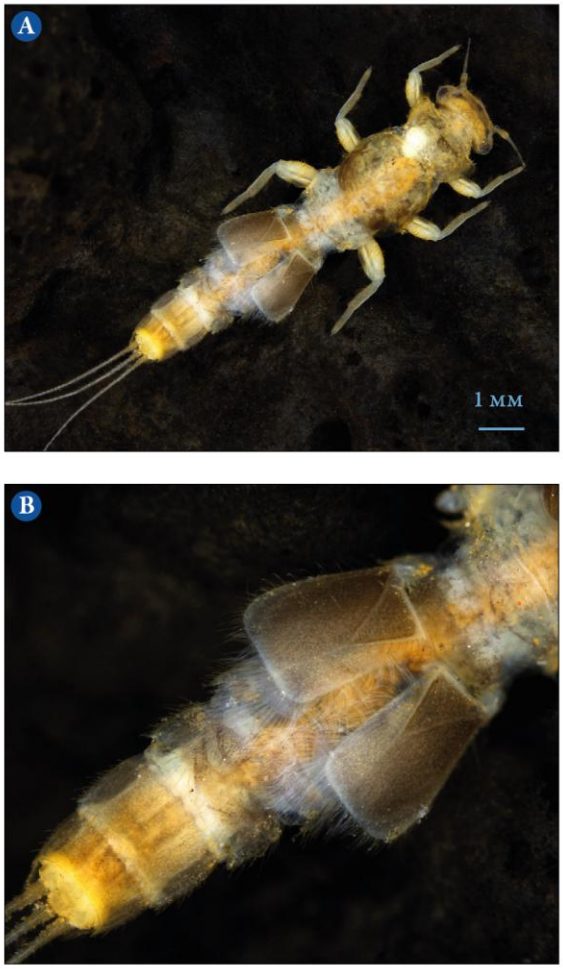

Figure 8: Caenidae nymphs with (A) the operculum, covering and partially protecting gills and (B) gills projecting behind the operculum.

Ecological notes: Nymphs are found in mud and amongst leaf litter, and are tolerant of mild pollution. On the Mambilla Plateau nymphs of Caenidae were found in forest fragment and open pasture streams.

Family: Leptophlebiidae

Nymphs often have flattened bodies (dorso-ventrally flattened) and may have large flattened heads (Fig. 9). However, unlike heptageniids the edges of the mandibles can be seen from above at the front sides of the head. A variety of gill shapes are found. Many gills are pointed and they are often bifid (two gills per segment), gills are easily lost. However, the posterior-lateral corners of the posterior abdominal segments typically have sharp points. "Tails" (or cerci) are long thin filaments, which also get broken easily. Some nymphs collected on the Mambilla Plateau resemble those of *Adenophlebioides***.** The body of nymphs can be 3–10 mm long.

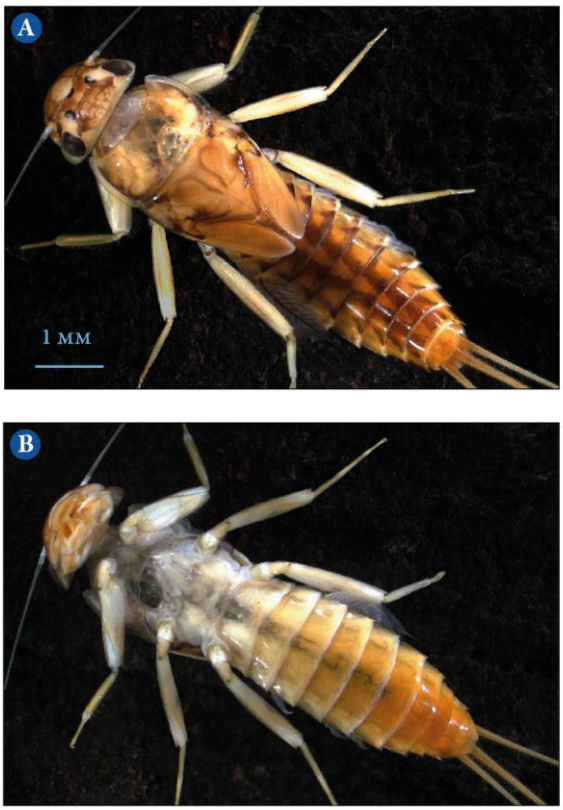

Figure 9: Leptophlebiidae nymph (A) dorsal view showing flat head and (B) ventral view with gill on display.

Ecological notes: Nymphs of Leptophlebiidae live under logs and boulders in streams with medium to high grade water quality. They are collector-browser or grazers, feeding on living or dead algae, or deposited fine particulate organic matter and are mostly found in forested streams on the Mambilla Plateau.

Family: Polymitarcyidae

Members of this family have nymphs, which burrow into fine and soft sediments with modified legs and mandibles (Fig. 10). The mandibles have prominent tusks that are digging structures. Gills of the nymphs lie over the abdomen (not at the sides) and have fringe edges. The genus *Povilla* has been recorded from Nigeria. Nymphs of another family, the Ephemeridae are very similar to those of Polymitarcyidae and may also occur in Nigeria.

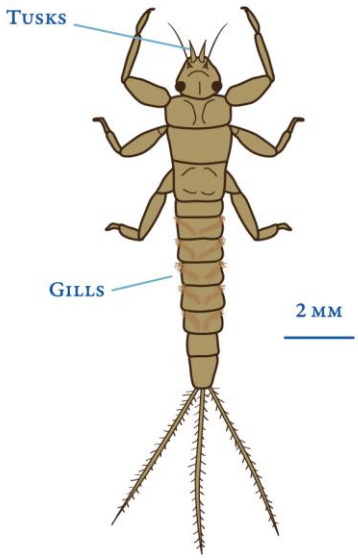

Figure 10: Polymitarcydae nymph showing gills over the abdomen.

Ecological notes: Polymitarcydae larvae were very rare but did occur in forested streams on the Mambilla Plateau. The nymph digs a tubular burrow through which it moves water using its gills. It feeds on particles from the water currents.

Order: Plecoptera (stoneflies)

Stoneflies are hemimetabolous insects with two tails, two tarsal claws on each leg, and long antennae (Fig. 11). Stoneflies may live several years, however, many tropical stoneflies can be expected to have short life cycles. In this study only the family Perlidae was found.

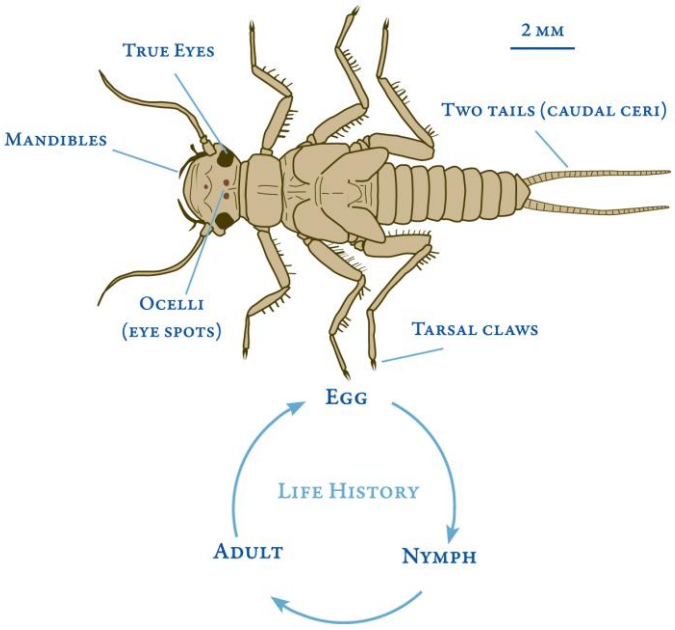

Figure 11: A generalised stonefly nymph and life history.

Family: Perlidae

A single genus, *Neoperla*, has been found on the Mambilla Plateau but it may be represented by more than one species. Nymphs have branched filamentous gills at the bases of each leg, and at the bases of the two caudal cerci ("tails"). The nymph (Fig. 12) resembles that of an unidentified *Neoperla* species reported in Nigeria by Ogbogu (2006).

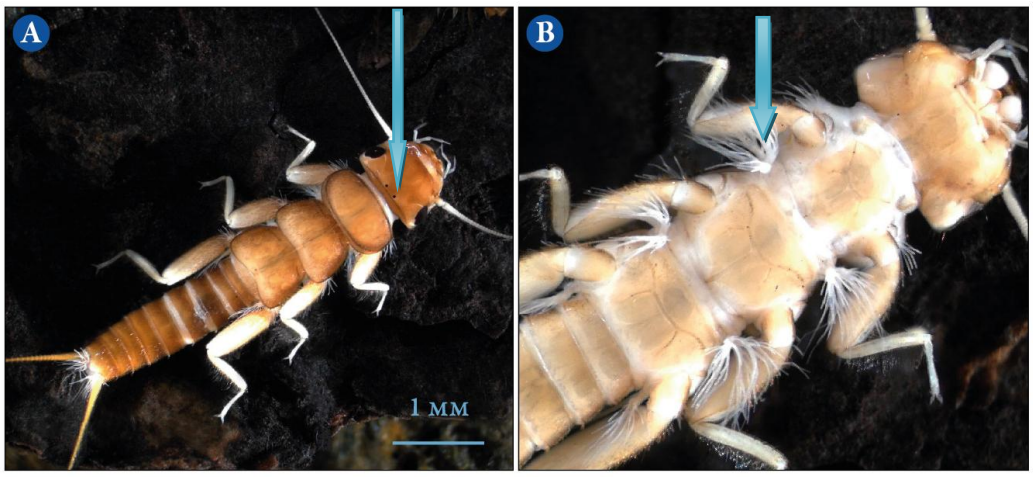

Figure 12: Perlidae genus resembling *Neoperla* showing (A) the pair of ocelli on the head, (B) filamentous gills, at the base of each leg.

Ecological notes: Nymphs are predatory and can be up to 30 mm long. They are common in high quality streams on the Plateau.

Order: Trichoptera (caddisflies)

Caddisflies are holometabolous insects, meaning the life cycle includes a larva, a pupa and an adult. Larvae have biting mouthparts with well developed mandibles, very small antennae, and the abdomen lack prolegs on its middle segments unlike the caterpillars of Lepidoptera. Many caddis larvae have portable cases made from sand grains, fragments of leaves and other materials. Others have a fixed retreat, whereas still others have no case or retreat and are described as free-living. A number of caddisflies can also have sclerotised thoracic segments.

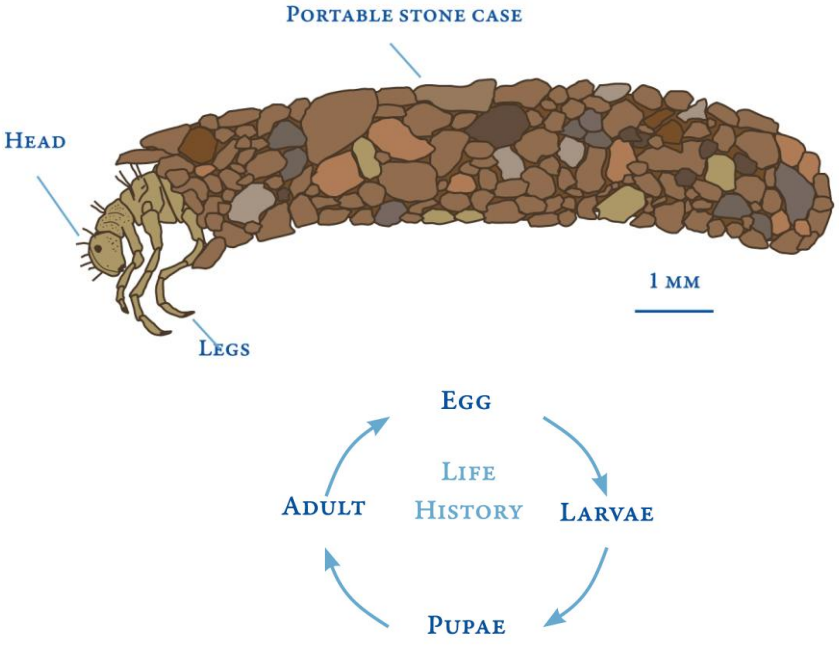

Figure 13: A generalised cased caddisfly and life history showing a pupal phase.

Family: Hydropsychidae (net-spinning caddis)

Several species belonging to this family, and the subfamily Hydropsychinae, occur on the Plateau. They can be recognised by the presence of branched gills on the ventral surfaces of seven or eight abdominal segments, and the prominent brush extending from the base of each anal claw. Larvae live in retreats (small stone houses) attached to rocks and wood and spin a capture net at the retreat entrance. Larvae are poor swimmers and may be up to 15 mm long.

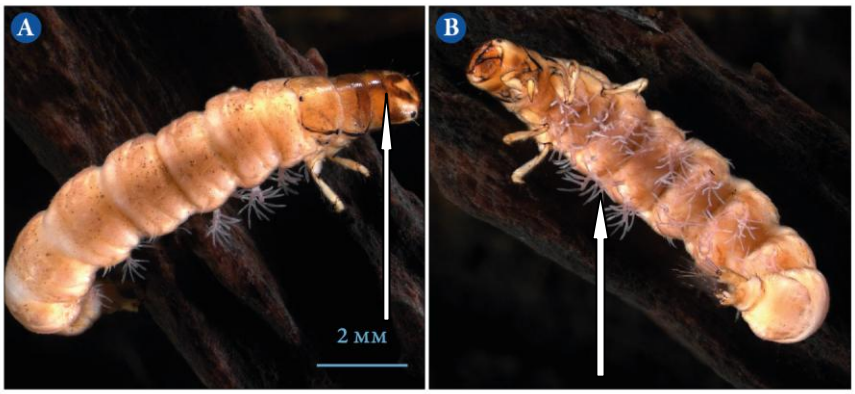

Figure 14: Hydropsychidae sp. A showing (A) pattern on the head (B) ventral view showing the branched gills.

Figure 15: Hydropsychidae sp. B (A) has no pattern on the head and (B) dorsal view.

Ecological notes: Hydropsychid sp. A (Fig. 14) has a pattern on its head and is confined mainly to forest, while sp. B (Fig. 15) has no pattern on its head and is found in both forest and pasture streams on the Mambilla Plateau. Gut content analyses revealed the presence of filamentous algae, diatoms and fungi. This suggests they may be mainly herbivores and possibly scrapers as well as filter feeders.

Family: Philopotamidae

Most philopotamid larvae (Fig. 16) are predominantly white and live in fine-meshed stocking-like retreats. They have no gills and can be recognised by the "T-shaped" labarum at the front of the head. Larvae are normally found in flowing water where water quality is high. The first segment behind the head has a hard plate (pronotal plate) but the other two thoracic segments do not have a plate. There are no tufted gills on the body. Larva are often found between

stones and in crevices, where they spin a silky tube. They are sometimes called 'Finger-net Caddisfly'.

Figure 16: (A) Philopotamidae larvae showing a pronotal plate but no other thoracic plates.

Ecological notes: On the Mambilla Plateau larvae were found within a silken net retreat, and were mainly confined to the forest and forest fragment streams. Algae and fine particulate materials were found in the gut.

Family: Polycentropodidae

Larvae may be free-living or occupy tubular retreats. They do not have a T-shaped labarum but have a pointed trochantin close to the base of the foreleg (Fig. 17). Larvae of free-living Polycentropodidae filter particles in the water by means of nets constructed from silk. Mesh size and configuration vary greatly among species and are related to the type of particle being trapped.

Figure 17: (A) Polycentropodidae larvae with three thoracic plates; pronotal, mesonotal and metanotal.

Ecological notes: Larvae were found in forest and forest fragment streams.

Family: Psychomyiidae

Larvae live on stones and wood in silken retreats that incorporate fine sand grains and detritus. Psychomyiidae (Fig. 18) have a superficial resemblance to Polycentropodidae but the trochantin at the base of the foreleg is shaped like the head of an axe. The first thoracic segment has a pronotal plate and there are no visible gills on the body. However, the head is somewhat enlarged compared to the rest of the body. It spins a silky tube with a net on stones.

Figure 18: Psychomyiidae larva.

Ecological notes: Psychomyiidae larvae were found in high quality flowing waters in the forest on the Mambilla Plateau.

Family: Leptoceridae

Larvae build a great variety of cases from pieces of wood, leaf fragments and mineral particles. The hind legs are very long. The family identity can be confirmed by examining the antennae, which although small are about six times as long as wide (Figs. 19 and 20).

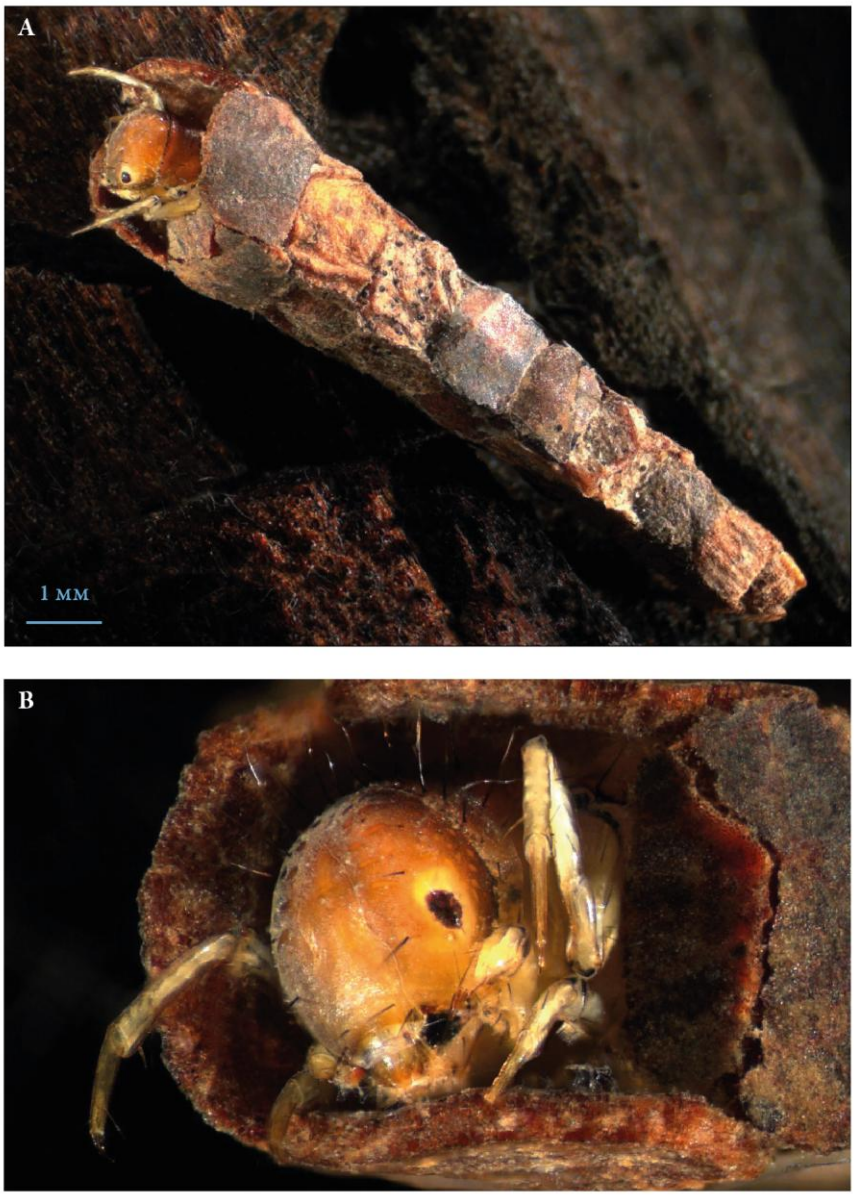

Figure 19: (A & B) Leptoceridae in portable leaf case.

Ecological notes: On the Mambilla Plateau leptocerids were found in forest, forest fragment and pasture streams. Larvae were found in slower sections of the water channel within leaf litter or macrophytes where fine organic debris accumulates. The case can be made of various materials e.g., fine gravel, leaves or small pieces of wood.

Figure 20: (A) Leptoceridae larva in a "log cabin" case made from wood (B) and larva using a mixture of fine sediment.

Ecological notes: Leptoceridae were found in forested streams.

Family: Glossosomatidae

Larvae build oblong cases out of sand grains and small stones (Fig. 21). Larva is usually found on the upper sides of stones where they scrape algae from the surface. Case length is up

to 15 mm and is made of stones. Glossosomatid larvae can be common in medium to high quality streams.

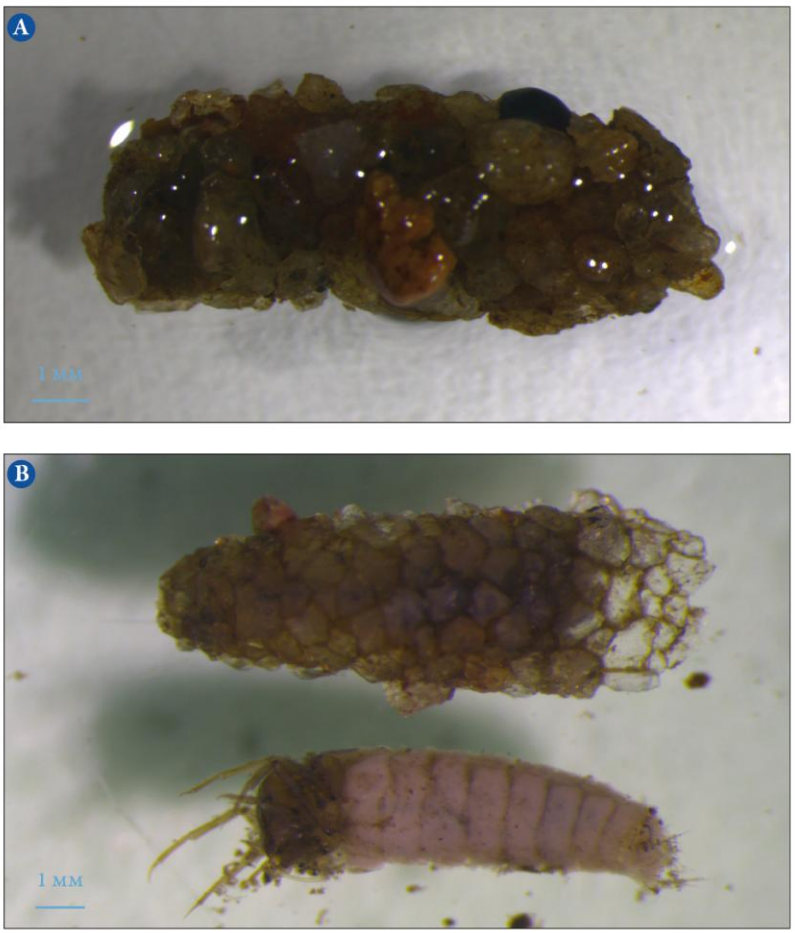

Figure 21: Glossosomatidae (A) pupal case, (B) case and larvae.

Ecological notes: On the Plateau glossosomatid larvae are found in both forest and pasture streams.

Family: Brachycentridae

The larvae shown below (Fig. 22) has a distinctive case constructed from two large pieces of leaf. Its identity as a brachycentrid is indicated by the long setae on the middle and hind legs and the lack of any dorsal or lateral humps on the first abdominal segment. This larva also has a distinct medially divided pronotum. The setae on the legs are used for filtering food materials from the water current, a habit occupied by many brachycentrid larva world-wide. Larvae are common in high quality streams and may have cases 12–25 mm long.

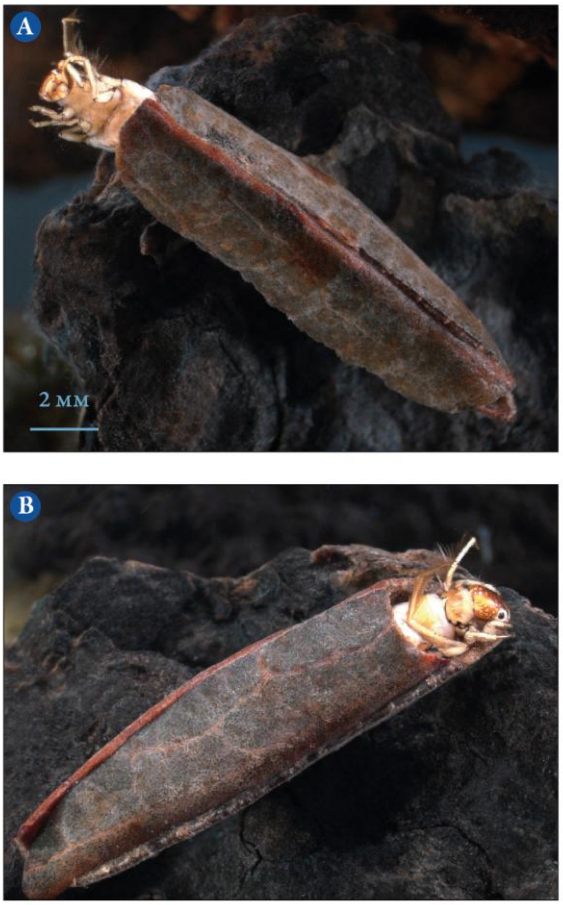

Figure 22: Brachycentridae larva (A) dorsal view and (B) ventral view.

Ecological notes-: On the Mambilla Plateau brachycentrid larvae are found mostly in shaded forested streams with high quality running water, and an abundance of wood and leaf packs.

Family: Hydroptilidae

Hydroptilids are some of the smallest caddisflies and are called micro caddis (Fig. 23). They have secreted cases that may be transparent, or incorporate plant material. Like hydropsychids, all their thoracic segments have well developed dorsal plates, which can be seen easily through the case if it is transparent. A hydroptilid found on the Mambilla Plateau is the very distinctive *Bibusa*, which incorporates filaments of red algae into the case.

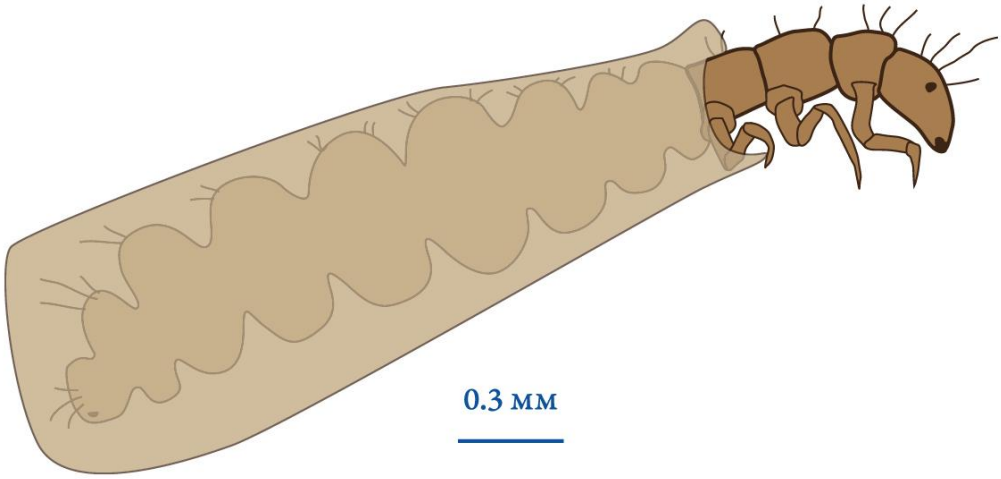

Figure 23: Generalised Hydroptilidae

Order: Odonata (dragonflies and damselflies)

Dragonflies (Anisoptera) are hemimetabolous insects and include some of the largest freshwater insects. They have an elongated, hinged labium (the dark mask), which is held beneath the head and over the face when at rest (Fig. 24). The labium is shot out to capture prey. Damselflies (Zygoptera) have a long, narrow abdomen terminating in three "tails" (caudal lamellae). In contrast, the abdomens of dragonflies (Anisoptera) are much broader and there are no caudal lamellae. On the Mambilla Plateau odonate larvae may have a body length up to 30 mm, and are most common in medium to high quality wetlands and pools. Dragonflies spend most of their lives as nymph in the water. Generally, this live about one year, but some take a shorter period while others may live as long as five years. When fully developed the nymphs will crawl onto the land to moult and emerge as adult insects. Dragonflies are formidable fliers and can catch prey in mid air. The adult may live from2-3 weeks to 2-3 months.

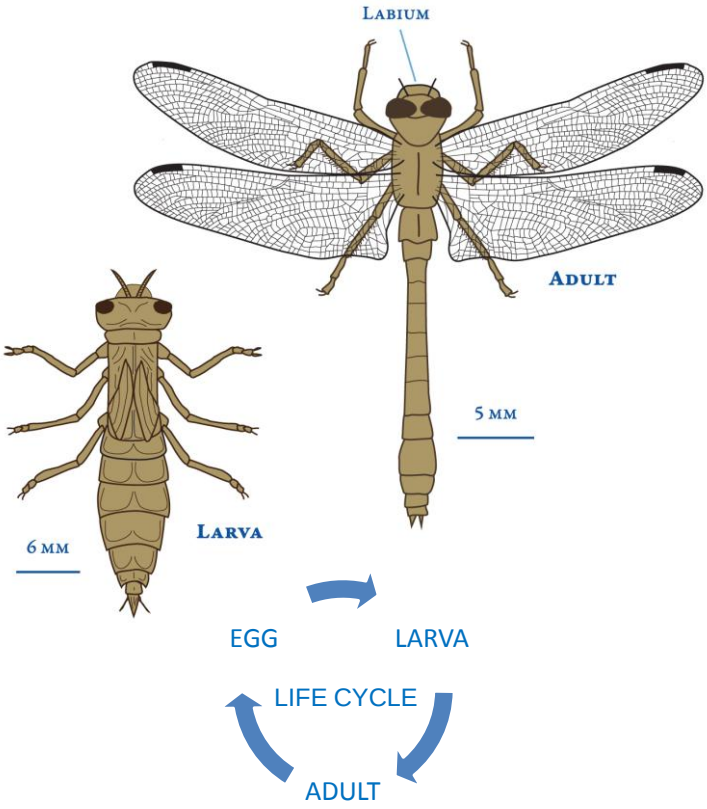

Figure 24: Generalised dragonfly larva and adult and life cycle.

Anisoptera (dragonflies)

Family: Gomphidae

The mask of gomphid larvae is almost flat and the abdomen is short and broad (Fig. 25). Features that can be used to identify gomphid are the 4-segmented antennae (the third segment is much longer than the others), and the 2-segmented tarsi of the middle legs.

Figure 25: Gomphidae (A) Dorsal view and (B) Anterior view.

Ecological notes: On the Mambilla Plateau gomphid larvae are common in both forest and pasture streams. They inhabit pools, in mud, underneath wood, stones or leaf packs. The mouth parts in addition to the mask are robust, of the biting type and well adapted for predation. Food items found in larva were mostly animal parts.

Family: Aeshnidae

Aeshnid larvae also have a flattened mask but the abdomen is elongate, the antennae have 6 or 7 segments and the tarsi of the middle legs have three segments (Fig. 26).

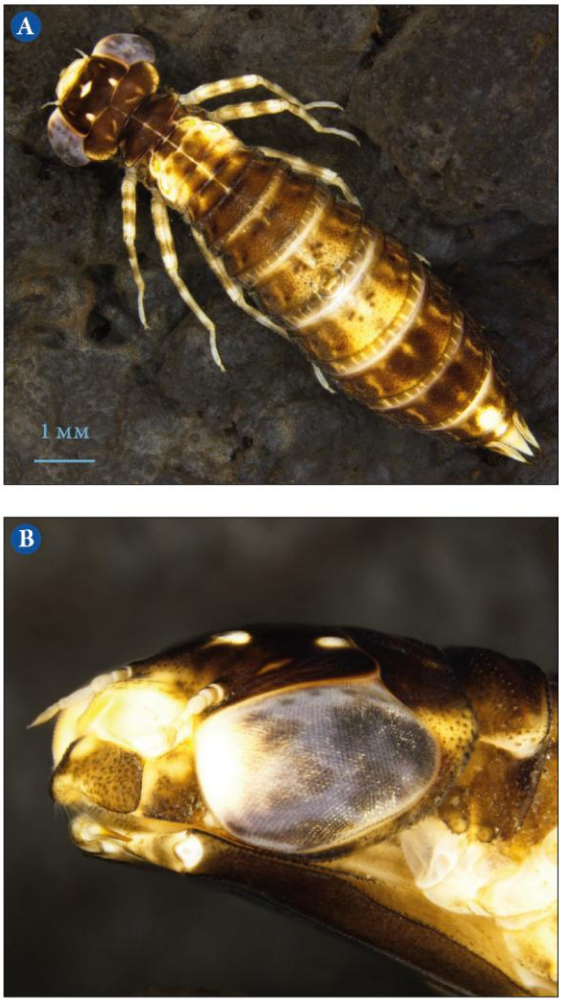

Figure 26: Aeshnidae (A) Dorsal view and (B) Ventral view.

Ecological notes: Aeshnid are common in medium to high water quality streams and pools which have a muddy bottom. Gut content revealed the presence of animal parts like chironomids, consistent with them being predators.

Family: Libellulidae and Macromiidae

Larvae are short and broad with a spoon-shaped mask (Fig. 27). The macromiids found on the Plateau had a distinctly patterned abdomen and thin striped legs (Fig. 28). Six species of Libellulidae in 3 genera were in light traps on the Mambilla Plateau (Umar *et al.*, 2012) indicating it is a diverse family.

Figure 27: Libellulidae (A) dorsal view and (B) Anterior view.

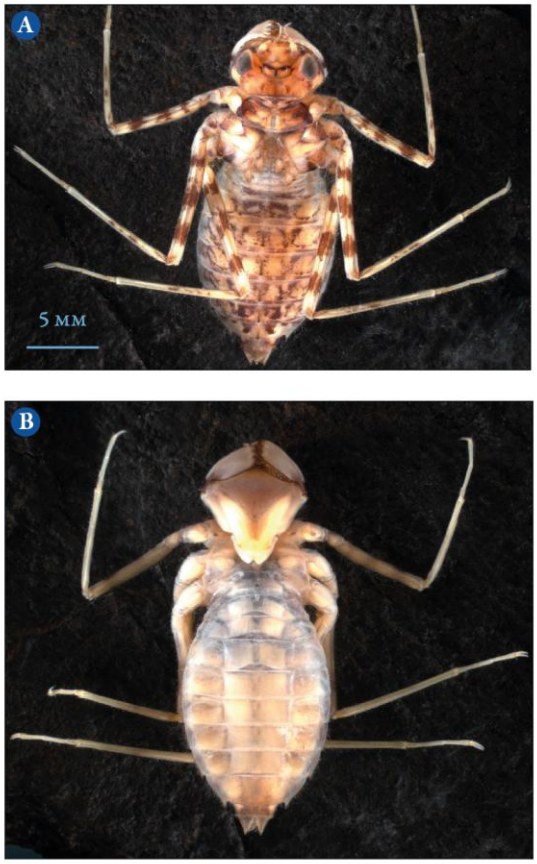

Figure 28: Macromiidae (A) Dorsal view and (B) Ventral view.

Ecological notes: On the Mambilla Plateau the larvae of Libellulidae were most common in pasture streams which are muddy with very low quality water and abundant macrophytes (Fig. 29). Members of the family Macromiidae tended to be more common in pasture streams, and were associated with very low quality water. They are found in burrows in mud or live beneath leaf packs and woody substrates.

Zygoptera (damselflies)

Family: Calopterygidae

Larvae are long and slender and the long first segment of each antenna is longer than all other segments together. Tend to be slimmer and less robust than other damselfly nymphs.

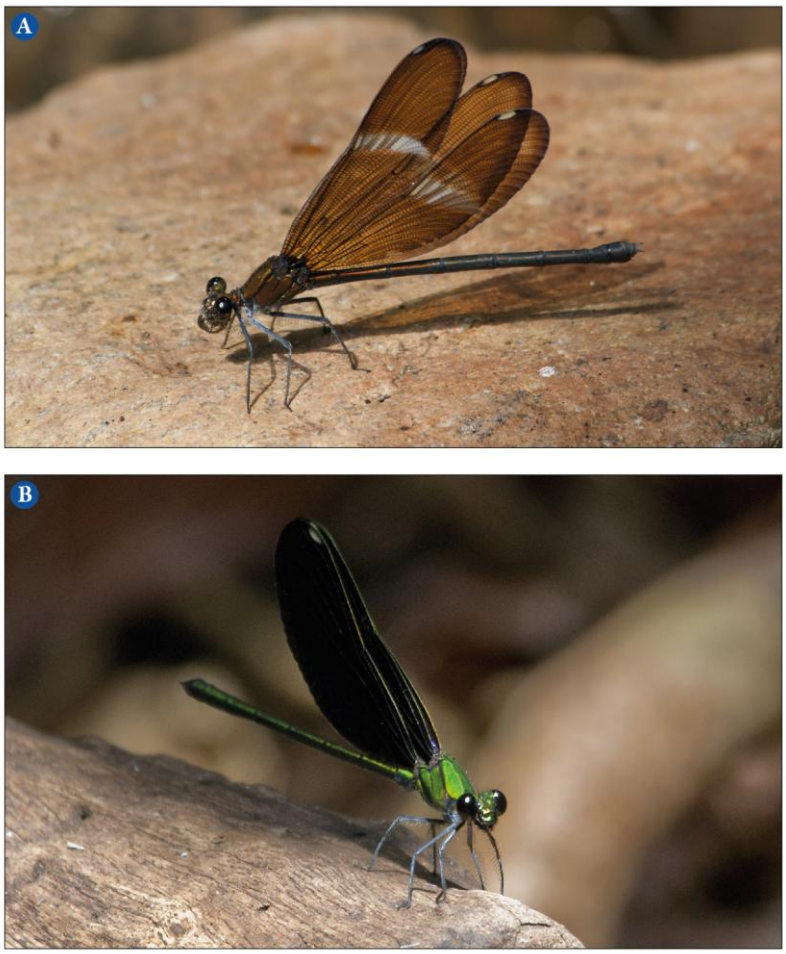

Figure 29: Adult zygopteras resting (A) female, (B) female. Their body length is about 50mm.

Ecological notes: Damselflies were very abundant in the pasture on the plateau, especially in grassland, where many pools and stagnant water bodies were quite common.

Order Coleoptera (beetles)

Beetles are holometabolous insects whose larvae and adults can be aquatic. However, pupation is usually on land. Most adult beetles have chewing mouthparts and hard wing covers (elytra) which meet in a straight line over the thorax and abdomen. Larvae show a wide variety of forms and typically have 3 pairs of jointed thoracic legs but no prolegs on the abdomen, also have no tails. Unlike many juveniles of other aquatic insect orders the beetle juveniles do not have distinctive "tails".

Family: Dytiscidae (diving beetles)

Both adult and larvae of dytiscids (Fig. 30) are aquatic. Adults have streamlined bodies and their legs may have long fringes of swimming hairs. The metasternum in front of the hind legs is covered by large plates often described as "wings", and are characteristics of the family. Larvae have an oval shape, hind legs with brushes of hair used for swimming. Several species have been found on the Mambilla Plateau including the large black *Dytiscus* which is about 12 mm long. Other species are less than 10 mm long and one has longitudinally striped elytra.

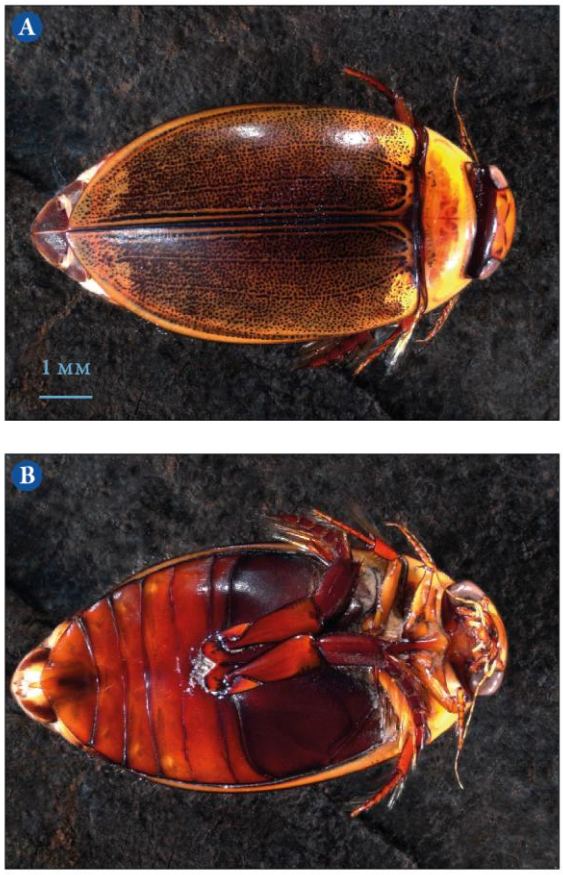

Figure 30: Dysticidae adult (A) dorsal view and (B) ventral view.

Ecological notes: On the Mambilla Plateau diving beetles are very common in ponds and streams. Food items found in their gut were mostly of animal origin, suggesting they are predators.

Family: Hydrophilidae

Hydrophilids are superficially like dytiscids and both adult beetles and larvae are aquatic. They can be fairly streamlined and may have swimming fringes on their legs. They can be easily distinguished from Dytiscidae by the form of the antenna. In Hydrophilidae the antenna is held beneath the head and has a 3-segmented club; in Dytiscidae the antenna project anterior-laterally from the head and have a regular filamentous shape. At least two species of *Deralus* have been collected on the Mambilla Plateau.

Ecological notes: Hydrophilids found on the Mambilla Plateau are small, and mostly occur in forest and forest fragment streams.

Family: Gyrinidae (whirligig beetles)

Whirligig beetles also have aquatic larvae and adults. Adults are strongly streamlined, shiny black and the middle and hind legs are like oars. They also have two pairs of large compound eyes. Both pairs are at the side of the head and lie above one another so that one pair looks up and the other down. This large beetle has tufted hair-like brush on the maxilla. At least 3 species of Gyrinidae have been collected on the Plateau including *Orectochilus* adults which were found in forested streams. Gyrinid larvae are elongate with a white abdomen and orange head and prothorax. The abdominal segments support pairs of long pointed lateral filaments, and there are 4 hooks on the last segment.

Figure 31: Gyrinidae *Orectochilus*

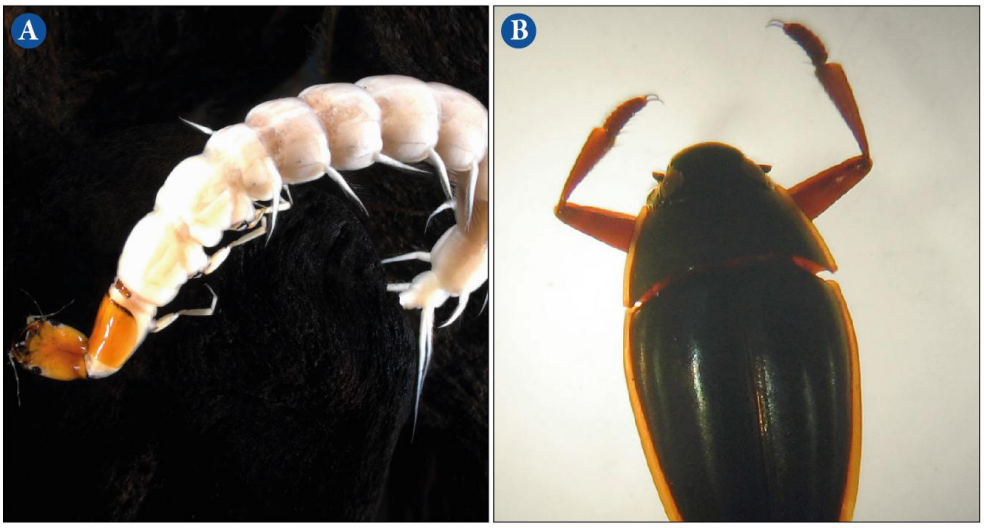

Figure 32: (A) Gyrinidae larvae and (B) adult beetle.

Ecological notes: Gyrinid can be confused with young dobsonfly larvae, but the head is much smaller. They are able to crawl rapidly on the stream bed. Gyrinid species are widely distributed in medium to high quality flowing streams on the Mambilla Plateau. They are mostly found in forest and forest fragment streams.

Family: Chrysomelidae

The yellow and black striped alligator weed beetle (*Agasicles hygrophila*) (Fig. 33) has been introduced to Nigeria and is found on the Mambilla Plateau. Beetles feeds on alligator weed and other plants that emerge above the water.

Figure 33: *Agasicles hygrophila*.

Family: Psephenidae (water penny beetles)

Only the larvae of Psephenidae (Fig. 34) are aquatic. They are highly distinctive being oval to round and flat with the head and legs invisible from above.

Figure 34: Pserphenidae larva dorsal view.

Ecological notes: Larvae are found attached to stony or wood substrates in flowing streams, with medium to high quality water.

Family: Scirtidae (marsh beetles)

Only the larvae of mash beetles are aquatic. They are small somewhat flattened, and have long multi-segmented antenna, which are easily broken. The thoracic segments are flanged laterally, and the abdomen narrows, posteriorly (Fig. 35).

Figure 35: (A & B) Scirtidae larvae (long antennae broken).

Ecological notes: On the Plateau the larvae found are somewhat flattened and/or elongate, with multi-segmented antennae usually longer than head and thorax. They are commonly found in pasture streams.

Family: Elmidae (riffle beetles)

Both the adults and larval stages of riffle beetles (Fig. 36) are aquatic, but only larvae have been found in freshwater on the Plateau. At least two species have been collected. They can be cylindrical or somewhat flattened and tapering posteriorly. The 9th segment of the larval abdomen encloses a chamber with a ventral operculum or covers that when open reveals gills and/ or hooks.

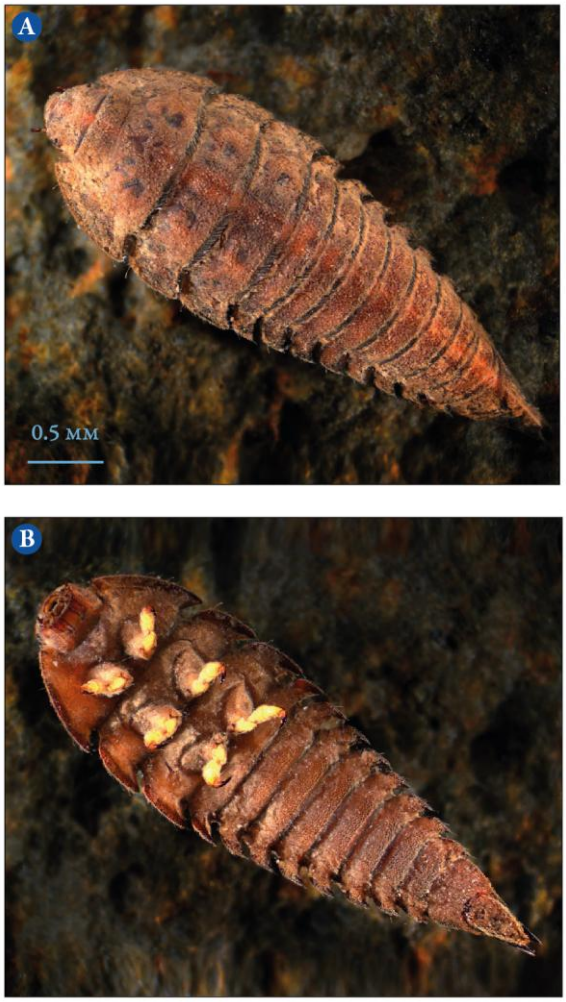

Figure 36: (A) Elmidae larva dorsal view and (B) ventral view.

Ecological notes: Elmidae larva have very variable body shapes; some are broad and flattened, some long and cylindrical. The elmids larvae found on the Mambilla Plateau were in the forest streams.

Family: Staphylinidae (rove beetles)

Few staphylinids are probably truly aquatic, but both adults and larvae of some species can be found associated with water. Adults have a distinctive body shape. Their elytra are very short and cover little if any of the abdomen. The elongate body has parallel sides, and the beaded antennae are longer than the head (37).

Figure 37: Staphylinidae adult.

Ecological notes: Staphylinids were found in the forest and forest fragment streams attached to macrophytes and other submerged plants.

Order: Hemiptera (bugs)

All aquatic hemipterans belong to the suborder Heteroptera, which is considered to be an order by some authorities. They are hemimetabolous insects with sucking mouthparts that are formed into a tube or rostrum.

Family: Belostomatidae (giant water bugs)

They can be large, ovoid, dorso-ventrally flattened insects with a body length greater than 18 mm. Their eyes protrude from the sides of the head and they have a pair of short, flat strap-like respiratory structures at the posterior end of the body. Belostomatids are predators. The species found on the Mambilla Plateau probably belongs to the genus *Belostoma* (fig. 38).

Figure 38: Belestomatid.

Ecological notes: Belostomatidae are fierce predators which stalk, capture and feed on aquatic crustaceans, fish and amphibians. They have also been found to capture and feed on baby turtles and water snakes Perez-Godwin (2006). They often lie motionless at the bottom of a body of water, attached to various objects, where they wait for prey to come near. They then strike, injecting powerful digestive saliva with their mandible, and sucking out the liquefied remains. Their bite is considered one of the most painful that can be inflicted by any insect, however, though excruciatingly painful, it is of no medical significance. Adults cannot breathe under water, and must surface periodically for air. Occasionally when encountered by a larger predator, such as a human, they have been known to "play dead" and emit a fluid from their anus. Due to this they are assumed dead by humans only to later "come alive" with painful results (Schuh and Slater, 1995).

Family: Naucoridae (creeping water bugs)

The ovoid, dorso-ventrally flattened naucorrids look rather like belostomatids, but are less than 16 mm long and have no posterior respiratory appendages. The head is wider than long and the rostrum is short and thick. The eyes of naucorids do not protrude from the sides of the head, and the femora of the forelegs are very broad (Fig. 39).

Figure 39: Naucoridae adult (A) dorsal view and (B) ventral view showing broad femora of forelegs.

Ecological notes: This water bug is widespread in shallow ponds with abundant vegetation on the Mambilla Plateau. Some adults have large wings covering the entire abdomen.

Family: Nepidae (water scorpions and needle bugs) (Figs. 40, 41)

Water scorpions and needle bugs have long, rigid posterior breathing tubes, and their antennae are shorter than the head. They are ambush predators and poor swimmers. Two genera are found on the Plateau: *Nepa* and *Ranatra*. The water scorpion *Nepa* has a broad, rather leaf-like body, whereas the needle bug *Ranatra* has a stick-like body.

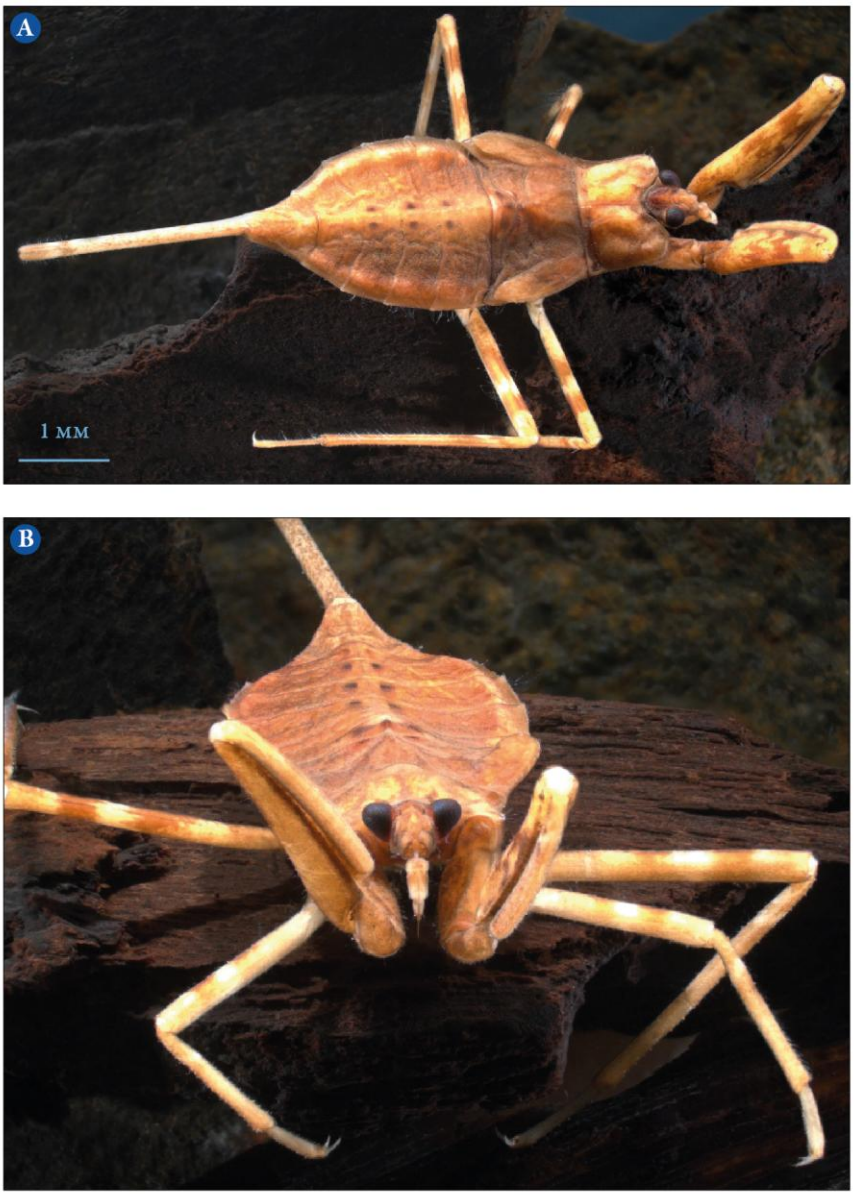

Figure 40: Nepidae (water scorpion), (A) dorsal view and (B) head with compound eyes and stylet.

Ecological notes: Water scorpions superficially resemble the poisonous terrestrial scorpion. One difference between the two is that the posterior siphon in the water scorpion is used for breathing not for stinging. Large front legs near the mouth are used for catching prey. Nepids are commonly found among debris in ponds and shallow waters in both the forest and pasture streams on the Mambilla Plateau.

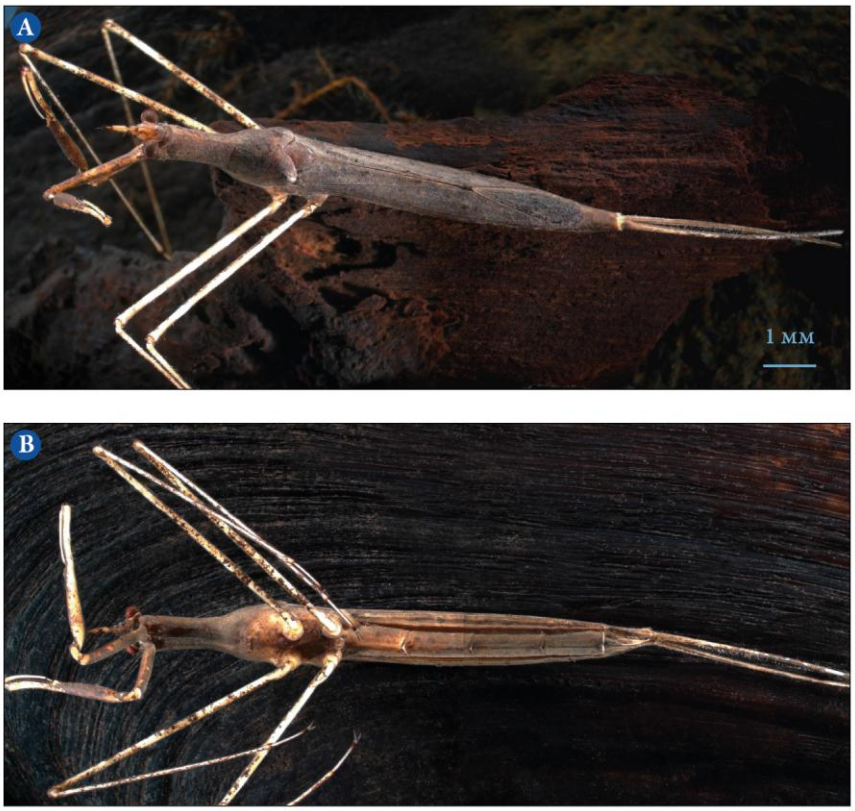

Figure 41: *Ranatra* (A) dorsal view and (B) ventral view.

Ecological notes: *Ranatra* seem to be most common among debris in ponds and shallow pasture streams which are open and have submerged grasses. They have tubular front legs used for catching prey. The front legs can appear like a pair of elongated jaws, giving the insect an appearance of just having four legs.

Family: Gerridae (water striders or pond skaters)

Water striders live on the surface of the water where they feed on insects and other invertebrates that are trapped in the surface film. They have very long, narrow legs (femora of the hind legs are particularly long) and claws inserted before the tip of the tarsus (Fig. 42).

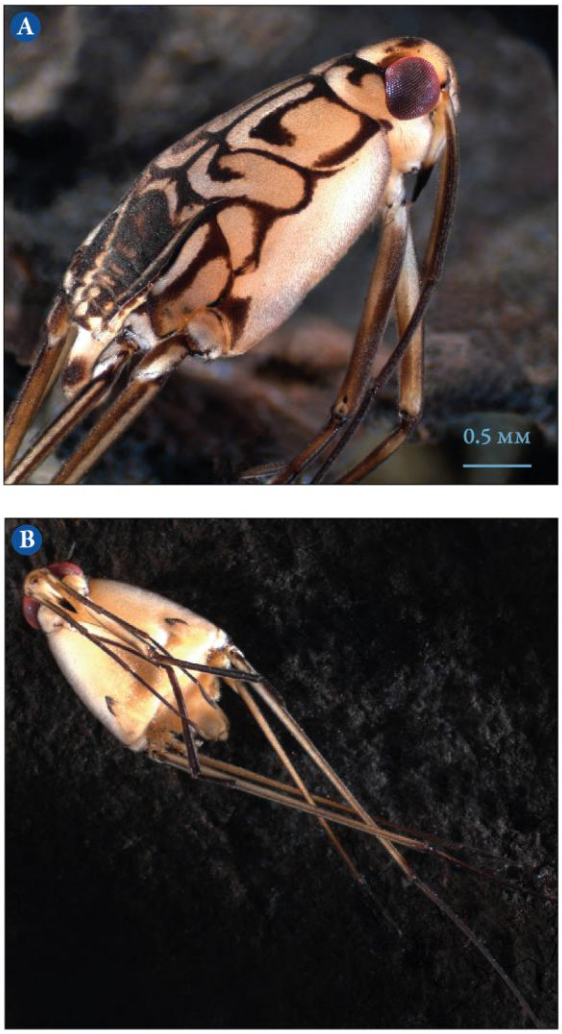

Figure 42: Gerridae adult, (A) dorsal view, (B) lateral view.

Ecological notes: Gerridae inhabit the surface of quite waters of streams and occasionally ponds, especially in pasture. They often have a short abdomen and the body may be long and slender or short and stocky.

Family: Veliidae (small water striders)

Vellids resemble gerrids but are smaller and have much shorter legs. They also live on the surface and have pre-apical tarsal claws. One genus of Veliidae found on the Mambilla plateau is *Rhagovelia,* distinguished by the plume of hair on the tarsi of the middle legs (Fig. 43). Nymphs of *Rhagovelia* resemble the adults but lack the tarsal plumes. Other genera of subfamily *Veliinae* also occur.

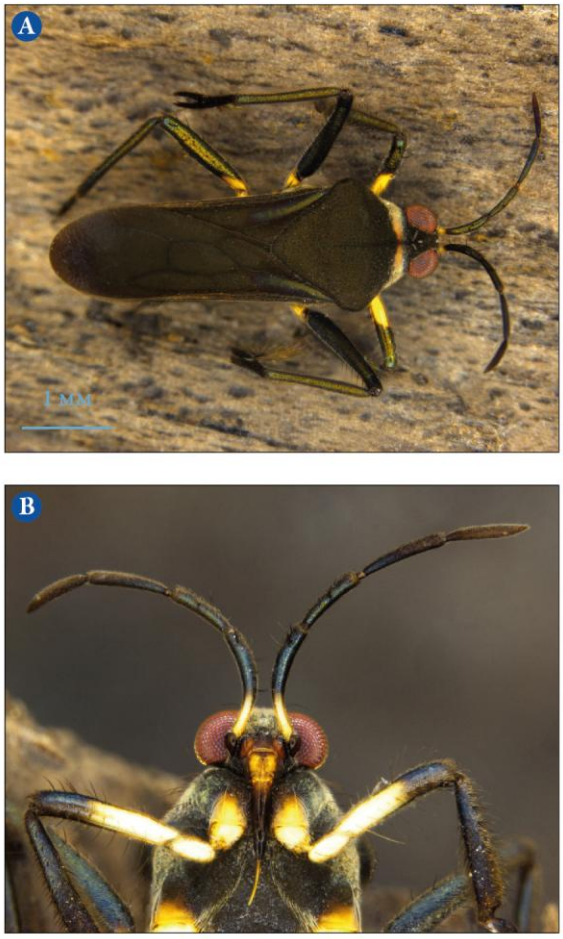

Figure 43: Veliidae *Rhagovelia* adult, (A) dorsal view and (B) head and antenna.

Ecological notes: Small water striders are found in large numbers at the surface of quiet waters of streams and occasionally ponds.

Family: Hydrometridae (water measurers)

Water measures are small, stick-like insects with an elongate head and exceedingly slender legs (Fig. 44). The antennae are longer than the head and the eyes are located about halfway along the head. Hydrometrids walk on the surface film of the water and on plants that project above the water. They were commonly found in the pasture streams.

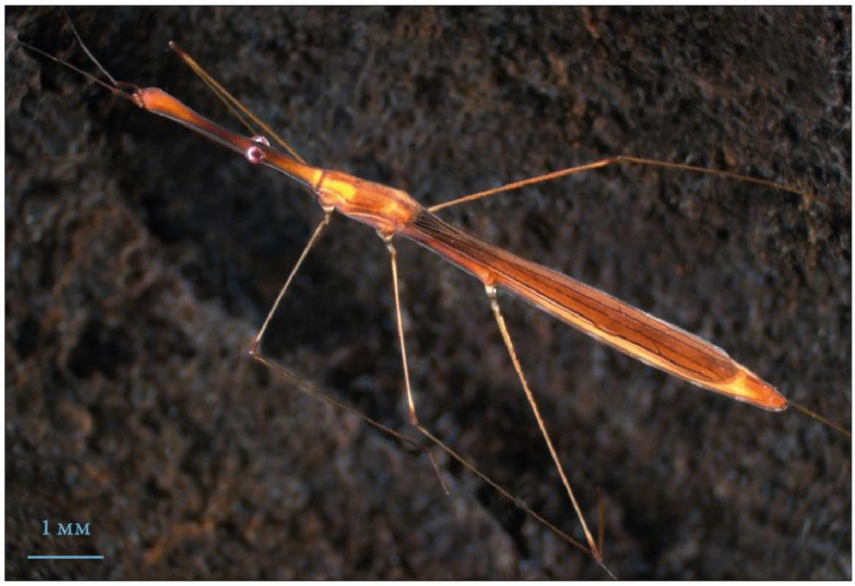

Figure 44: *Hydrometra* (A) dorsal view and (B) grassland stream.

Ecological notes: Hydrometra is very hard to spot, especially in streams with emerging or submerged grasses.

Family: Corixidae (water boatmen)

Water boatmen are dorso-ventrally flattened and have a short broad rostrum beneath the head. The forelegs are modified as "scoops", the middle legs have a large terminal claw for grasping plants, and the hind legs are fringed with swimming hairs. Species found on the Mambilla Plateau belong to the tribe Corixini: and are 5–7 mm long (Fig. 45).

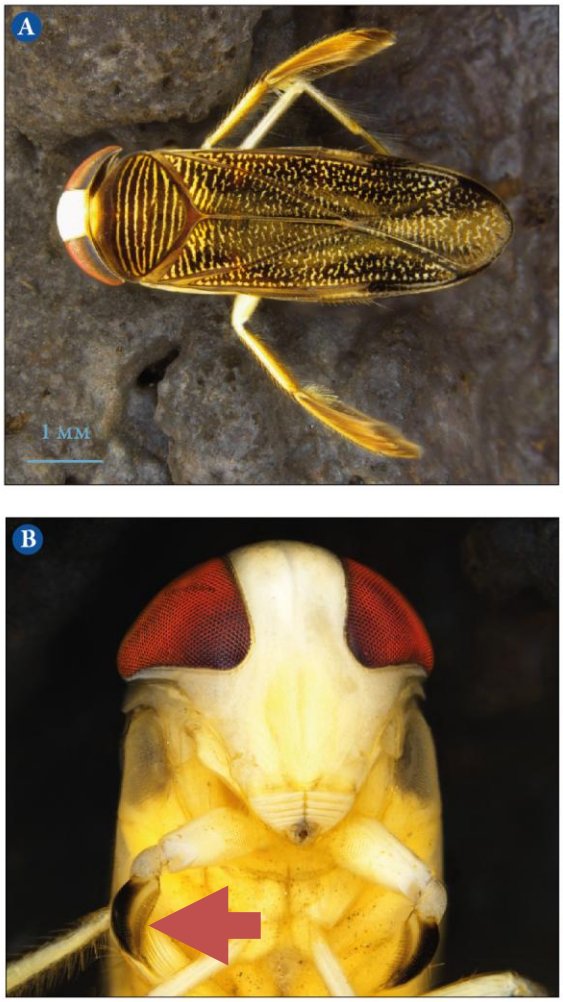

Figure 45: Corixidae adult, (A) dorsal view and (B) head (ventral) and scoop-like fore-tarsus used to feed on plant material.

Ecological notes: Corixidae inhabits ponds and deep pools of streams, frequently surfacing for air. The hind legs have a fringe of hairs used for swimming.

Family: Notonectidae (back swimmers)

Like corixids, back swimmers are strong swimmers (Fig. 46). They are not dorso-ventrally flattened and swim ventral-side up using the long, fringed, hind legs as oars. They have a longer, more pointed rostrum than water boatmen and feed on other insects and small crustaceans.

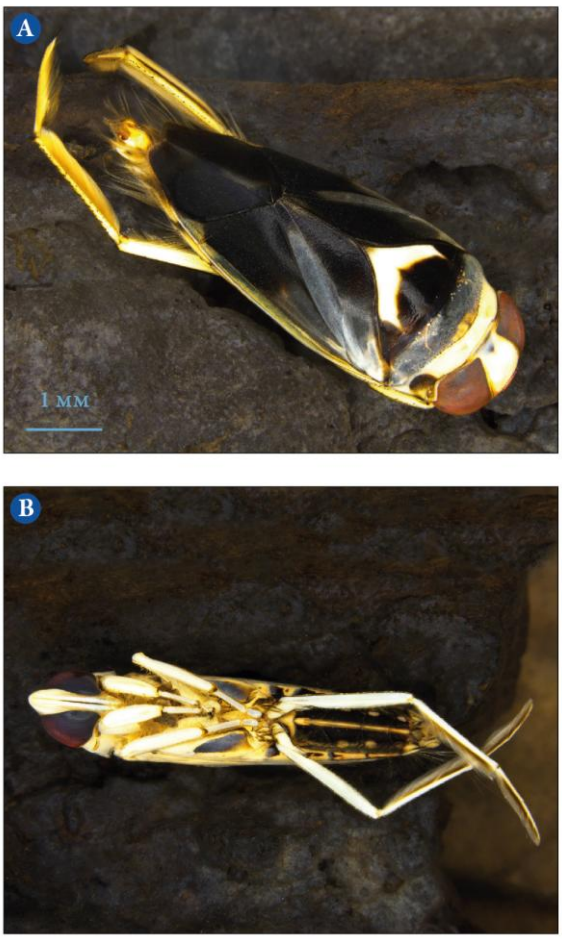

Figure 46: Notonectidae adult, (A) dorsal view and (B) ventral view.

Ecological notes: Backswimmers inhabits ponds and deep pools of streams, frequently surfacing for air. On the Mambilla Plateau they are found mostly in pasture streams with deep pools.

Family: Gelastocoridae (toad bugs)

Toad bugs have short, broad bodies and are about 10 mm long. The head is wider than long and the prothorax even broader. The femora of the fore-legs are very broad, and the tibio-tarsus ends in a point (Fig. 47).

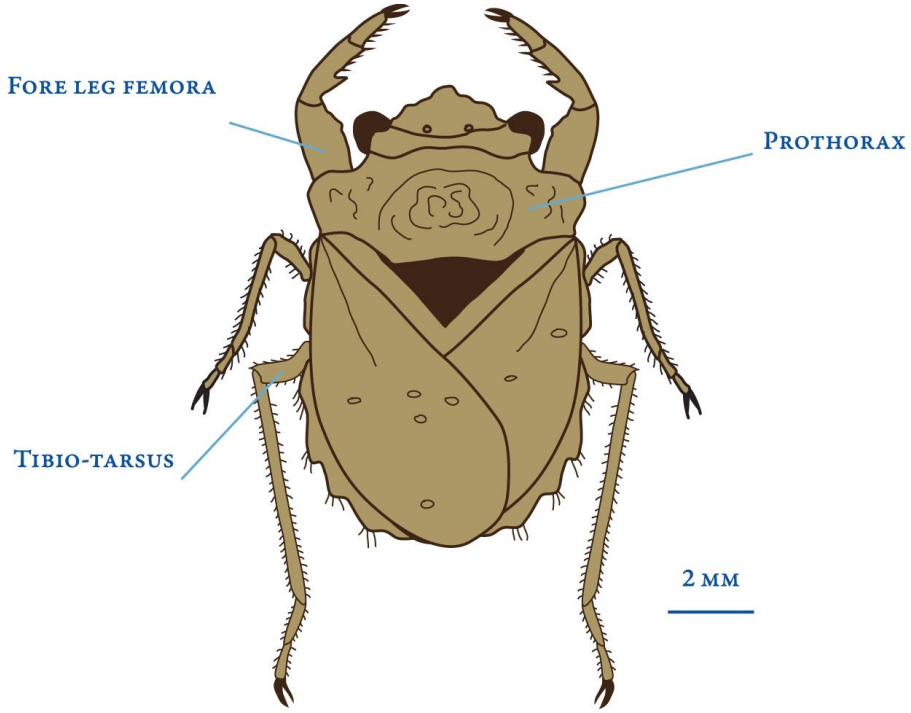

Figure 47: A generalised diagram of toad bug.

Figure 48: Wet mud and debris.

Ecological notes: Toad bugs are predators that live at the edges of water bodies but can crawl into the water. Commonly known as 'toad bugs' Gelastocoridae species occur on the ground and in the leaf litter in a variety of habitats, from both wet and dry sclerophyll forests to open healthland habitats. They are considered to be semi-aquatic species occurring in riparian and

littoral areas of lentic water bodies or very slow-flowing areas of rivers. They are found under stones and plant debris or burrowing into wet sand or mud (Fig. 48).

Order: Diptera (true flies)

Larvae and sometimes pupae of numerous dipterans are aquatic. They are a diverse group with many families represented. Because they have no jointed thoracic legs, dipterans larvae can be distinguished from larvae of other aquatic insects. Many are maggot- or grub-like with mouth-hooks and no true head, whereas others have a well developed head. Eight different families were identified on the plateau.

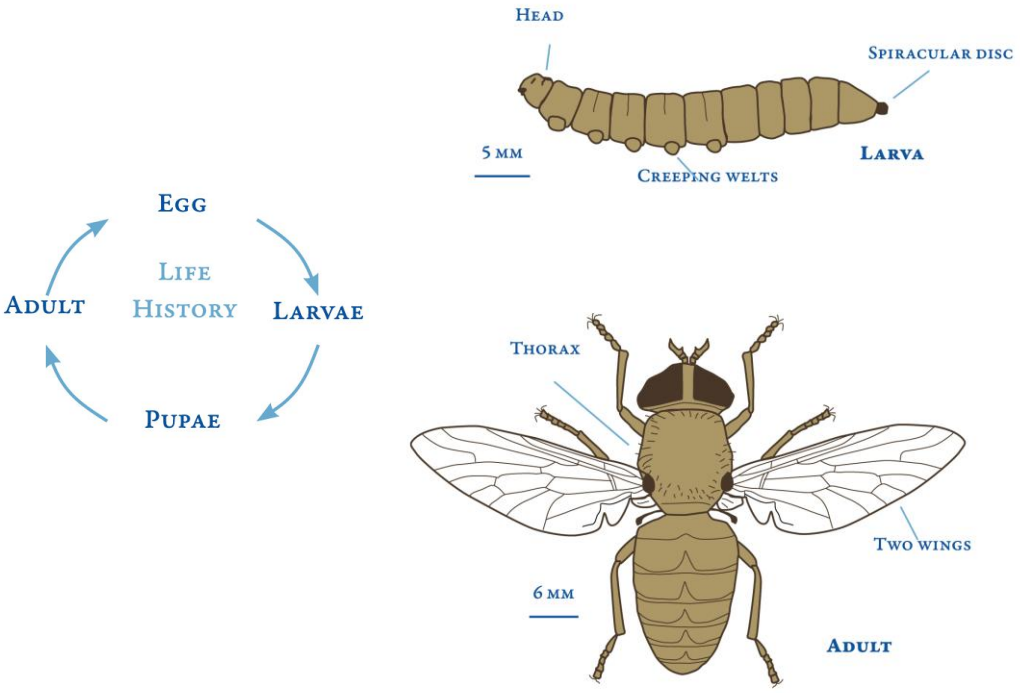

Figure 49: Life history and generalised dipteran larva and adult.

Family: Tipulidae (craneflies)

Tipulidae have a partially complete head that can be retracted into the thorax. A spiracular disc is variably present at the posterior end of the abdomen and may be surrounded by several lobes and long hairs. Some larvae have caterpillar-like creeping welts, their body length is up

to 30 mm. Tipulids can be common in high, medium, or low quality water. The large larva shown (Fig. 50) belong to the subfamily Tipulinae and may be a species of *Leptotarsus*. Other tipulids found on the Mambilla Plateau belong to the subfamily Limoniinae and include representatives of the tribe Hexatomini (Fig. 51).

Figure 50: Tipulinae? *Leptotarsus*; (A) Crane fly larva and (B) spiracular disc.

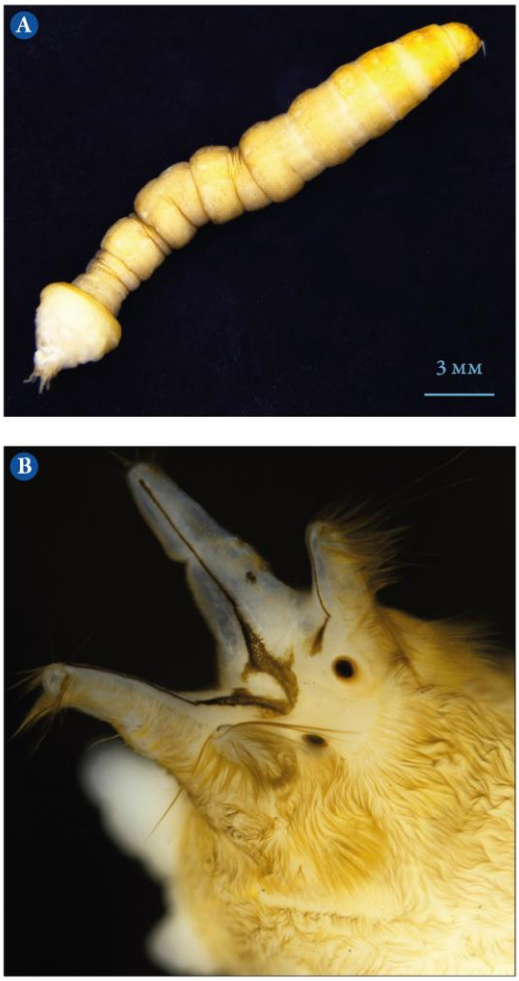

Figure 51: (A) Limoniinae; Hexatomini larvae (B) spiracular disc with spiracles (C) spiracular lobe.

Ecological notes: Tipulids larvae inhabit ponds and deep pools of streams. They are found in medium and low quality water and are tolerant of some degree of organic pollution.

Simulidae (black flies)

Black fly larvae are easily recognised by their unusual shape, they have a swollen abdomen, a relatively large head, and single thoracic prolegs. Labral fans that extend from the head are used for filter feeding while the larva remains attached to the substrate with tiny hooks. Body length is up to 5 mm. The genus found in Nigeria is *Simulium* (Fig. 52).

Figure 52: *Simulium* larvae, showing labral fans.

Ecological notes: The larvae and pupa inhabit running waters with rocky substrates. Larvae can be common in high, medium or low quality streams. The adult of the species *Simulium damnosus* is known as a blood sucker and is the vector of a parasitic nematode (*Onchocerca volvulus*), which causes the disease onchocerciasis or river blindness in some parts of Nigeria, including the Mambilla Plateau.

Family: Culicidae (mosquitoes)

Larvae have a swollen thorax and a caudal breathing tube (siphon) at the tip of the abdomen. Larvae are often called wrigglers because of their characteristic swimming motion. Pupae swim with a tumbling motion, and are often found with larvae. Body length is usually less than 4 mm (Fig. 53).

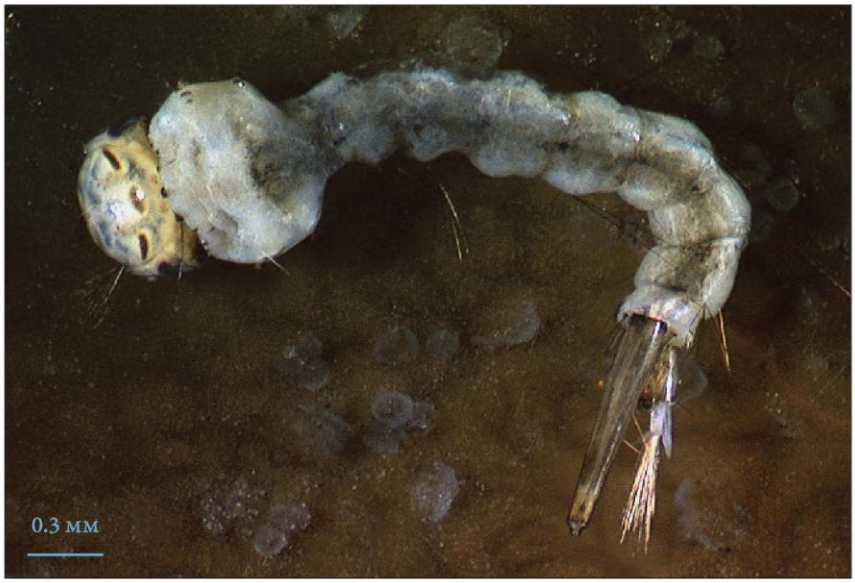

Figure 53: Culicidae (mosquito larvae).

Ecological notes: Mosquito larvae prefer standing waters of streams or pools. These insects are also carriers of vectors of human diseases such as malaria. On the Mambilla Plateau larvae of Culicidae are common in both the pasture and forest streams.

Family: Chironomidae (non-biting midges)

The small worm-like larvae have a distinct sclerotised head and pairs of thoracic and posterior prolegs. Some larvae are bright red (especially in low oxygen environments) because of the presence of haemoglobin. Some larvae inhabit tubes that are attached to the substrate, whereas others are free-living and can crawl or swim with a "thrashing" motion. Body length is up to 20 mm, although most larvae are less than 10 mm. Chironomids are common in high, medium and low quality streams as well as still waters. Members of the sub-families Chironominae (e.g., *Chironomus,* Tanytarsini) and Tanypodinae (tribe Pentaneurini) have been found on the Mambilla Plateau (Fig. 54). No species of Orthocladiinae were found.

Figure 54: Chironomidae larva

Ecological notes: Chironomid larvae were found in both forested and pastures streams, especially in slow running water with sandy substrates associated with aquatic macrophytes.

Family: Ceratopogonidae (biting midges)

Larvae found on the Plateau are narrow, worm-like insects with a dark, bullet-like head. A rosette of fine hairs surrounds the posterior tip of the abdomen. Larvae swim in an eel-like manner and are assumed to be predatory (Fig. 55).

Figure 55: (A) Ceratopogonidae and (B) Chironomidae: Tanypodinae.

Ecological notes: Larval gut analysis of Ceratopogonidae revealed presence of animal parts. They were most commonly found in forest and forest fragment streams.

Family: Syrphidae (rat-tail maggots)

Rat-tail maggots may be 15–20 mm long and are broad and blunt anteriorly (Fig. 56). They have a very long, posterior, extensile breathing tube (siphon). Syrphids often occur in heavily polluted waters.

Figure 56: Syrphidae (rat-tail maggot).

Ecological notes: On the Mambilla Plateau the rat-tail maggot is most common in the pasture streams, especially in the grazing land associated with streams highly polluted with livestock waste.

Family: Athericidae

Larvae have pairs of proleg on the first seven abdominal segments. The eighth segment bears a single prolegs and a pair of fringed dorsal projections. Larvae are predatory and feed on other insect larvae (Fig. 57).

Figure 57: Athericidae larvae.

Ecological notes: The larvae of the Athericidae are small and were very common in polluted streams with poor water quality.

Family: Psychodidae (moth flies)

The thoracic and abdominal segments of most moth fly larvae have secondary annulations ("pseudo segmentation") and often dorsal plates on many of these annuli. Spiracles on the tips of the posterior projections are surrounded by hydrophobic hairs that keep the water out when respiring at the surface (Fig. 58).

Figure 58: (A) Psychodidae larva.

Ecological notes: Psychodidae larvae were often associated with polluted water.

Phylum: Arthropoda

Subphylum: Crustacea

Crustaceans are a highly diverse group of arthropods with a hard exoskeleton and often with more than three pairs of jointed appendages. They are distinguished from insects by having two pairs of antennae (the first pair often called antennules).

Order: Decapoda

Infraorder: Astacidea (crayfish)

Nigerian freshwater crayfish belongs to the family Astacidae, and include the genera *Astacopsis*.

The first 3 pair of walking legs are chelate (have pincers), the first pair being large. Crayfish also have long, prominent antennae, a long straight abdomen, and a broad tail-fan. Body length is usually less than 150 mm. Crayfish are common in medium to high quality streams.

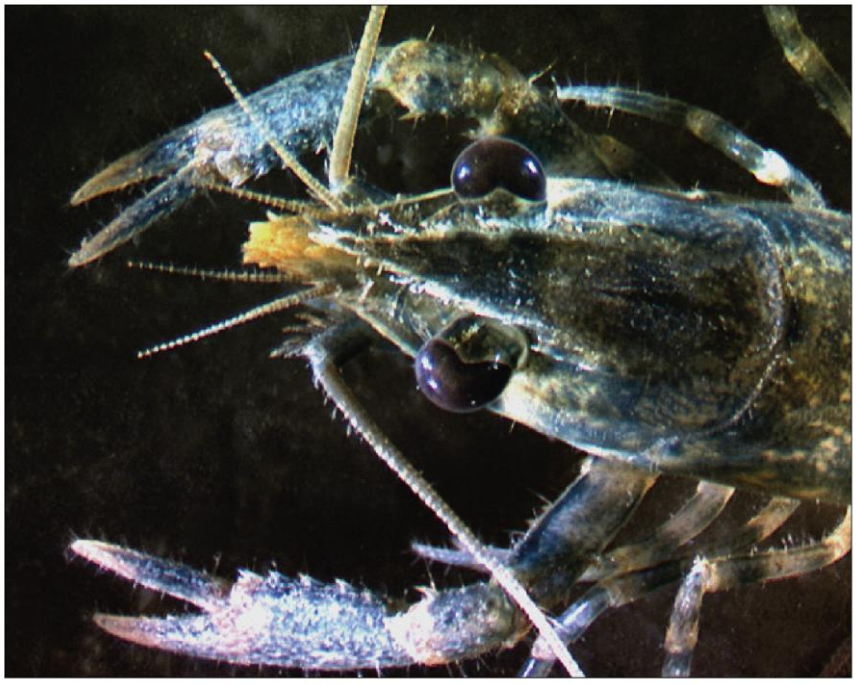

Figure 59: Crayfish.

Ecological notes: Freshwater crayfish are omnivorous and live in high quality running water. On the Mambilla Plateau crayfish are abundant in the forested streams, but are also found in some forest fragment streams with medium grade water quality.

Infraorder: Caridina (shrimps)

Shrimps are strong swimmers with the body compressed laterally a little. The first two pairs of legs are chelate but neither pair is particularly large. Shrimps found on the Mambilla Plateau have tufts of hairs at the tips of the first two pairs of walking legs and therefore belongs to the family Atyidae.

Figure 60: Atyidae (shrimps).

Ecological notes: On the Mambilla plateau shrimps are widespread in streams with medium to high quality water.

Infraorder Brachyura (crabs)

Crabs are dorso-ventrally flattened with a large hard carapace covering the body except the head. The first pair of legs has a large chela. The abdomen is short and folded beneath the carapace-covered thorax so it cannot be seen from above. Eyes are on stalks and the antennae are very short (Figs. 61, 62). The principal family of freshwater crabs in Nigeria is the Potamonautidae, which has 80 species in 11 genera. Crabs are common in slow-flowing streams and some Nigerian species occur in forested areas (Dobson, 2004).

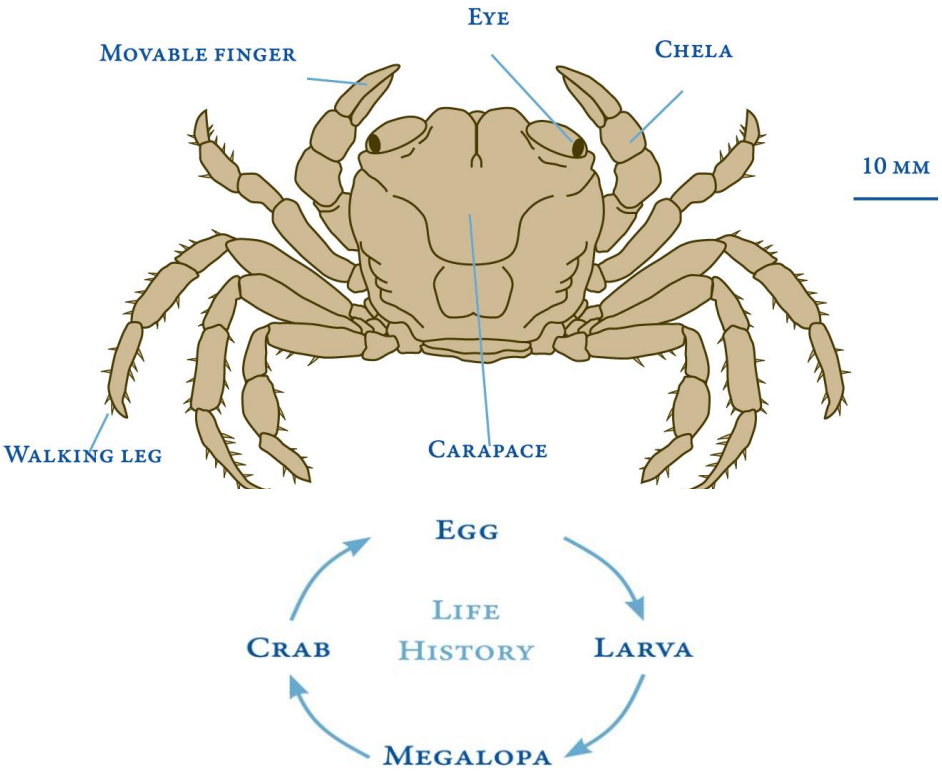

Figure 61: Nigerian freshwater crab drawing and life history.

Figure 62: Brachyura: Potamonautidae (crabs).

Ecological notes: On the Mambilla Plateau crabs are found mostly in the forest and fragments, beneath woody substrates, in leaf packs and amongst sand or gravels. Leaf materials were the major food item found in their gut, indicating their role as shredders.

Smaller Crustaceans

Several groups of small crustaceans are found in Nigerian streams. Due to their small size, such taxa were not commonly collected, and were not identified. They are not considered in this guide.

Phylum: Platyhelminthes

Order: Tricladida (flatworms)

Flatworms are very common in freshwater but are often overlooked because of their small size (generally less than 6 mm long) and drab appearance. They are usually grey or black lack segments, and are elongate-oval in shape (Fig. 63). Flatworms are strongly flattened and have a rudimentary "head" with a pair of visible eyes. They move with a gliding motion, and can be common in high, medium, and low quality streams.

Figure 63: Tricladida (flatworm).

Ecological notes: Flatworms slide over the stream bed to feed on dead animals or hunt soft-bodied animals, which may be swallowed whole. They respire by the diffusion of air directly through the skin. The severed parts of some flatworms can grow into new individuals.

Sub-class Hirudinea

Leeches have long very contractile, multi-segmented bodies with suckers at both ends. They move with the help of the suckers, and by extending the body. The body colour of leeches can be grey, brown or green (Fig. 64).

Figure 64: Leech (A) ventral view and (B), dorsal view.

Ecological notes: Leeches lives on the stream bed either on soft silt or amongst stones. Some leeches suck the blood of fish or frogs, whereas others feed on small animals such as worms, molluscs, or fly larvae. Some leeches can eat more than their own body weight in one meal. Body length is typically 10–60 mm.

Phylum: Annelida

Class: Oligochaeta

Oligochaetes are segmented worms with 4 sets of chaetae on each segment (visible only with a microscope). Aquatic species resemble small earthworms but most are in different families (Fig. 65). The most common family is the Naididae (which now includes Tubificidae). They frequently colonise soft sediments and may be very abundant in poor quality, polluted waters.

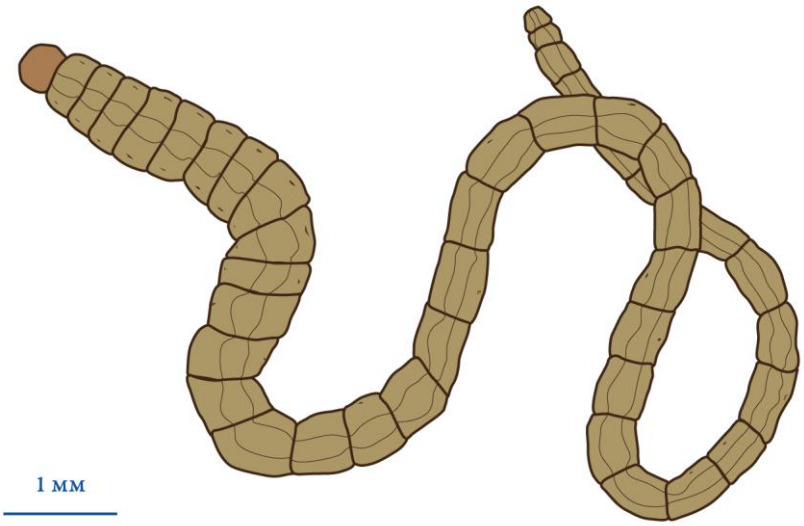

Figure 65: A generalised segmented worm.

Phylum: Mollusca

Freshwater molluscs have one or two shells (valves) and no legs. The class Gastropoda contains the species that live in a single shell; the class Bivalvia, those with two valves. Some species have the ability to tolerate a wide range of osmotic pressures and salinities and are described as euryhaline (Winterbourn, 1973).

Gastropod families known from Nigerian freshwaters include Lymnaeidae, Planorbidae, Physidae, Ampullaridae and Thiaridae. However, in this study only two families were collected: Planorbidae and Thiaridae. The large conical species (Fig. 66) is the thiarid *Melanoides tuberculatus*, an introduced species that is now widespread and abundant in many parts of the world. The upper whorls of the shell have a trellis pattern of crossing spirals and transverse ridges and are brown in colour, although adults can have black incrustations, and an eroded apex. The shell grows to 38 mm high. The globular species (Fig. 67) is the planorbid *Bulinus globosus* which is widespread in many freshwaters in Nigeria. Its shell is up to 5 mm in height and is a brown-yellow colour. *B. globosus* is known to be an intermediate host of the trematode *Schistosoma mansonii*, which causes the schistosomiasis in humans.

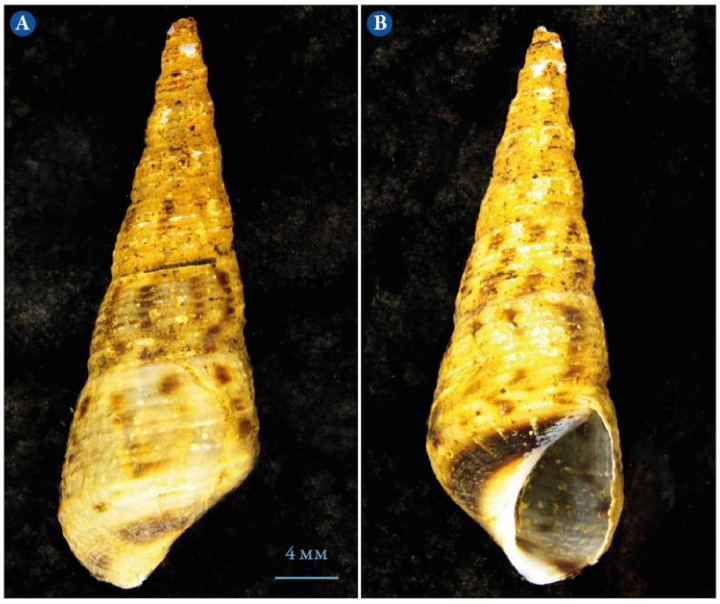

Figure 66: (A) *Melanoides tuberculatus* and (B) the aperture mouth and columella area.

Ecological notes: *Melanoides tuberculatus* is widely distributed in ditches, ponds, rivers and streams (Haynes, 1984). On the Mambilla Plateau it's commonly found at agricultural sites, e.g. maize and tea streams. In these streams, algae are common and provide food. The presence of macrophytes probably provides protection from being washed away by water currents.

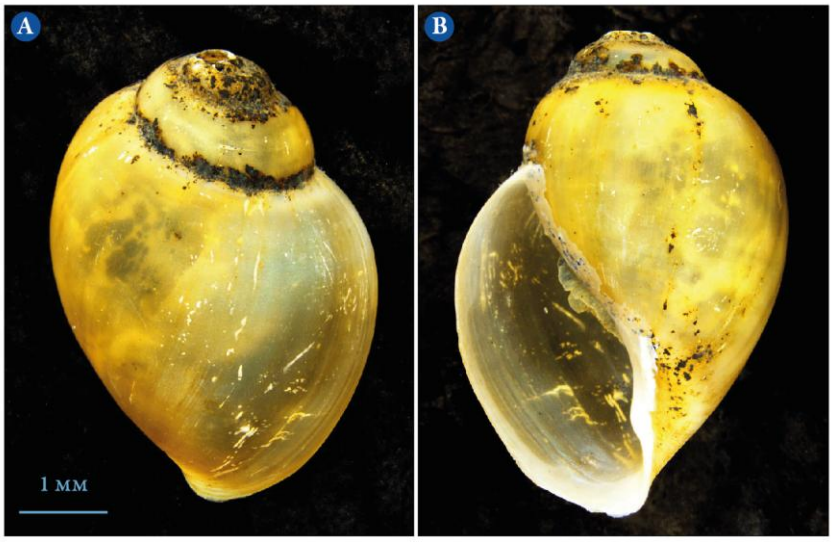

Figure 67: (A) *Bulinus globosus,* showing body whorl and globe-like shape and (B) aperture.

Ecological notes: On the Mambilla Plateau *Bulinus globosus* is found mainly in agriculture streams with very low quality water e.g., cabbage, maize and grazing streams.

Glossary

Abdominal – segmented posterior section of the arthropod body behind the thorax; lacking jointed legs, but sometimes with pseudopods or prolegs.
Anal – posterior segment
Anal claw – a claw on the posterior segments of the abdomen (often in caddis larvae).
Annulations – rings
Antenna (e) – sensory structure usually on the most anterior part of the head.
Anterior – the front of the body
Bifid – divided in two, e.g. two gill plates joined together
Carapace – the hard shell (exoskeleton) e.g., in crabs
Caudal – anal or posterior end (of the body)
Caudal filament – threadlike process at the posterior end of the abdomen, as in mayfly nymphs and dobsonfly larvae.
Caudal lamella – plate-like projections at the end of the abdomen, as in a damselfly larvae
Cerci – tail projections or filaments
Chelate – claw-like or pincer-like
Compound eye – eye made up of numerous sensory units and lens systems.
Dorsal surface – upper or top surface
Elytra – the hard wing covers of an adult beetle.
Euryhaline – tolerant of wide range of salinities
Exoskeleton – the outer scleritized plates (or cuticle) of arthropods.
Femur – the third segment of the leg
Filamentous – long and thin
Hemimetabolous – with incomplete or partial metamorphosis from larva to adult. Without a pupal stage.
Holometabolous – with complete metamorphosis from larva to pupa to adult.
Hydrophobic – water repelling
Labral fans – labral mouth parts seen in blackfly larvae to enable filter-feeding of fine
Lateral – side
Lentic water – standing water, e.g. a pond or lake.
Littoral – the shallow sides of a stream, pond or lake.
Mandibles – the jaws or equivalent mouthparts
Maxillae – a lateral pair of mouthparts
Medial – in the middle (of the body)
Metanotum – dorsal surface of the third thoracic segment.
Metasternum – the plate on the ventral (under) surface of the metathorax.
Nymph – the juvenile stage of an aquatic insect that has a hemimetabolous life cycle.
Operculum – a plate or "trapdoor lid" in molluscs that seals the opening of the shell
Palps – processes (often multi-segmented) forming part of the mouth parts of arthropods.
Proleg – a simple, fleshy "leg" without true segments. Often with terminal hooks or crochets.
Pronotum – the first dorsal plate on the (pro) thorax or "chest" segment. It sits directly behind the head.
Pupa – an intermediate life stage where the insect changes from larva to a winged adult. Pupation is the act of turning into a pupa.
Rostrum – a forward extension of the carapace at the head, usually in Crustacea
Sclerotized – hardened
Setae – hairs, often sensory
Spiracular disc – a breathing structure with openings for tracheae found in aquatic flies
Sternal region – ventral side
Tarsi (us) – the last segment of legs. The last tarsal segment often ends in a claw.
Thorax – the body section between the

particles from the water column.

Labial mask – the modified labium of damselflies and dragonflies that sits below the head at rest, and can be shot forward to capture prey.

Labium – the "lower" lip.

Labrum – the "upper lip". A mouthpart associated with the labium, maxilla and mandibles.

Larva (e) – the juvenile stage of an aquatic insect that has a holometabolous life cycle.

head and abdomen and to the legs and wings are attached. The thorax consist of three segments; the prothorax, mesothorax and metathorax.

Tibia – the 4th leg segment, between the femur and tarsus.

Trochantin – a plate often found next to the base of the leg in caddisfly larvae.

Valves – the two shells of a mussel or clam.

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Chapter three

Response of benthic invertebrate communities to a land use gradient in tropical highland streams in Nigeria

Introduction

Land use activities is an important issue globally, and has been recognised as a key cause of the contamination of many stream environments. The degradation of lowland rivers, particularly by prolonged agricultural activity, has received international recognition (Bunn *et al.*, 1999; Harding *et al.*, 1999; Feld and Hering, 2007). Agricultural activities have been shown to affect stream ecosystems in various ways that include changes to nutrient loadings (Allan *et al.*, 1997), solar energy flux, and sediment inputs (Robbins and Edgington, 1975; Kemp and Thomas, 1976; Madej, 2001).

Despite many improvements in land management, tropical streams are under increasing land use pressure from activities including overgrazing, bush burning, deforestation, agricultural intensification, mining and irrigation (Tripler *et al.*, 2006; Solomon *et al.*, 2009). All of these activities are of particular concern in Africa. Despite these pressures, the effects and mechanisms by which these land use activities influence stream communities in Africa are not well documented. In Nigeria several studies have focussed on anthropogenic issues, such as the effects of domestic waste, sewage (Ogbogu and Olajide, 2002; Arimoro *et al.*, 2007; Arimoro and Ikomi, 2008), urbanisation (Emere and Nasiru, 2007) and heavy metals contamination (Odo, 2007).

However, studies on the effects of land use activities on stream invertebrate communities are limited. Victor and Ogbeibu (1985) investigated benthic communities in fourth order streams flowing through farmlands in southern Nigeria. They recorded some invertebrate taxa, however, the whole river system was physically disturbed (Victor and Ogbeibu, 1985).

Arimoro *et al.* (2008) reported the effect of cassava effluents on macroinvertebrates communities along the Orogodo River in the Niger Delta, Nigeria. They found that the overall density of fauna differed significantly between an upstream unimpacted site and a downstream site where cassava effluents were present and resulted in the dominance of oligochaetes and dipterans (Arimoro *et al.*, 2008).

Increasingly, benthic invertebrates have been used as indicators of ecosystem conditions (e.g., pollution levels and ecosystem health), because they are easy to sample and may respond to changes more rapidly than larger aquatic organisms such as fish (Gibbson and

Funk, 1982). They have been used as pollution indicators in tropical streams in Asia (Dudgeon, 2000; Blakely *et al.*, 2010) and Africa, for detecting changes in the quality of freshwater systems (Gibbson and Funk, 1982; Rosenberg and Resh, 1993; Crown *et al.*, 1995; Ajao and Fagade, 2002).

The relatively limited taxonomy of benthic invertebrates in the tropics, especially Africa presents additional challenges for researchers. The aquatic larval stages of many insects have not been associated with adults and identification to species is often not possible (e.g., Pearson and Boyero, 2009; Boyero *et al.*, 2009). In Nigeria a number of studies have attempted to review aspects of the tropical Nigerian aquatic fauna (Egborges, 1993; Eyo and Ekwonye, 1995; Ogbeibu and Oribhabor, 2002), however, no comprehensive identification guides or pollution metrics been produced.

Studies on ecosystem dynamics in Nigeria are lacking due to inadequate research efforts by scientists who have been faced with numerous problems. Common among these problems include lack of infrastructure, research grants and poor funding for faculties in research institutions. Others are a lack of freshwater science education, non-utilization of research results and political issues. Ogbogu (2013) suggested that solving these problems encountered by freshwater scientists in the region should start by eliminating or reducing the impact of these challenges. This has become imperative if the global climate change and its impacts on the West African freshwater ecosystems are to be fully understood and managed (Ogbogu 2013).

The macroinvertebrate fauna of tropical streams is generally similar to that found in temperate streams, because most of invertebrate orders occur universally (Hynes, 1970). However, tropical stream communities do have some distinctive characteristics that distinguish them from streams at temperate latitudes. These differences are generally at the family, genera and species level and occur as some families and genera are significantly more diverse and numerically dominant in the tropics. Several insect orders (e.g., Odonata, Hemiptera and Trichoptera) can be very diverse in tropical streams whereas the Plecoptera seem restricted to the family Perlidae. Few families are known to be exclusively found in the tropics and in Africa currently only the Prosopistomatidae (Ephemeroptera), Pseudoneureclipsidae (Trichoptera) and the Heterotrephidae (Heteroptera) are thought to be restricted to afrotropical streams (Jacobsen *et al*., 2008). Jacobsen *et al*., (2008) compared the tropical fauna of South-east Asian and South American tropical streams and observed that the same insect families; the Baetidae, Leptophlebiidae, Chironomidae, Hydropsychidae and Elmidae dominated in streams in both regions. Furthermore, studies of tropical streams

indicate that shrimps are common and have important roles as grazers, predators and detritivores (e.g. Pringle *et al.*, 1993; 1993; Pringle, 19996; Pringle and Hamazaki, 1998; Crowl *et al.*, 2001; March *et al.*, 2001, 2002). Similarly freshwater crabs (primarily Potamonautidae) are widely reported from tropical (and afrotropical) streams (Dobson *et al*., 2002). Insects dominate the stream fauna in all tropical regions as is the case in many temperate streams. In Africa insects can exceed 90% of the community in forested and cultivated sites along the Segana River, Kenya (Mwangi, 2000).

Thus although we know that tropical stream communities may differ in composition from temperate streams, our understanding of how land use activities effect the fauna is limited. This study investigated the response of benthic stream communities to variable land use activities in tropical highland streams on the Mambilla Plateau, in south eastern Nigeria.

Methods

Study area

The study was conducted in the tropical montane region of the Mambilla Plateau, in the south east corner of Taraba State, Nigeria (11º- 6º E and 6º- 7º N). The Plateau is at an altitude of approximately 1500m a.s.l. and the rainy season lasts for an average of 250 days, from late March to the end of October. In contrast, from November to mid-March the region is relatively dry and may be affected by the harmatan (a dry cold north - south wind) between December and January. Mean annual rainfall exceeds 1780 mm, peaking in June and July, however due to the high elevation of the Plateau the daily mean temperature rarely exceeds 30ºC. During the study mean air temperature was 24^{o}C. All streams sampled were near the village of Yelwa in the headwaters of the Donga River (Fig. 1).

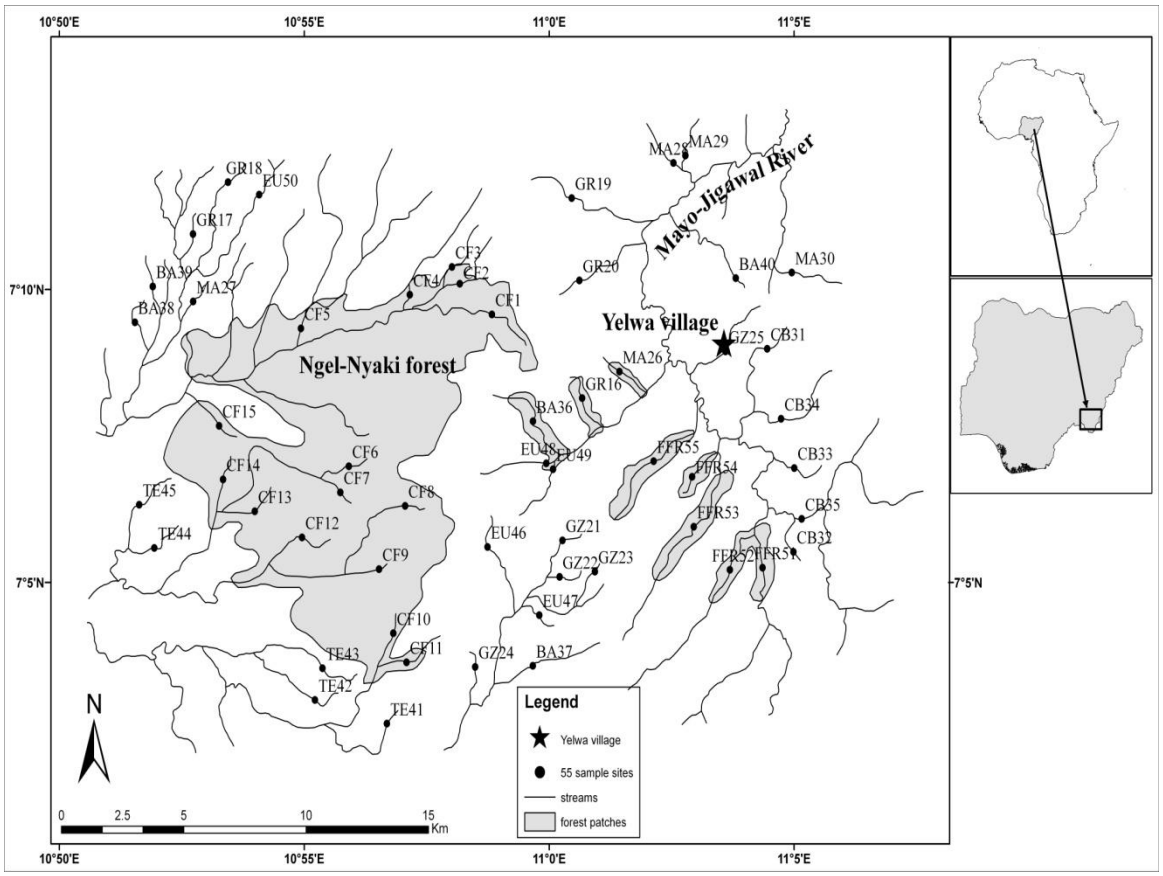


Figure 1: The Mambilla Plateau is situated in the north-east of Nigeria. The 55 study streams were located near Yelwa village and Ngel-Nyaki Forest Reserve (CF = continuous montane forest, FFR = riparian forest fragment, EU = Eucalypt, TE = tea, BA = banana, GZ = grazed, GR = grassland, MA = Maize, CA = cabbage).

The most pristine streams occured in the tropical montane area of the Ngel Nyaki Forest Reserve. The forest reserve is 52 km^2 and includes 7.5 km^2 of continuous forest. The terrain is steep and there has been no deforestation. The forest was dominated by mature trees including *Deinbollia pinnata, Santiria trimera, Rafania* sp., *Croton macrostachyus, Anthonotha noldeae* and *Ficus* sp., whereas in the intensive grazed pasture land, trees such as *Acacia senegalensis, Polyscius fulva, Beeilschmedia* sp., *Pouteria altissima* and *Bridelia speciosa* occured. Local history of the Vogel Peak Massif and the Mambilla Plateau suggest that the Fulani people, who were primarily cattle farmers brought their cattle in numbers to these areas in the early 19th century. Since then, the Mambilla Plateau has been burned and overgrazed (Hall, 1971). Grazing across the Plateau is facilitated by extensive annual burning of grasslands and erosion and sediment deposition in streams is common. Over the last few decades planting of *Eucalyptus* (for firewood) and tea plantations has been prevalent.

A total of 55 headwater streams (first and second order) were surveyed from October 2009 to March 2010. Initially at least five replicate streams were selected in each land use and

crop type, however in the final analysis streams were assigned into four different land use categories; continuous tropical montane rainforest (15 streams), riparian forest fragment (5 streams), plantation (15 streams i.e., including five tea, five banana and five *Eucalyptus*) and crops and pasture (20 streams i.e., five cabbage, five maize, five grazing, and five grassland). In the continuous and forest fragments streams substrates were dominated by gravel, cobbles and sand (on average 15% gravel, 25% cobbles, 20% pebbles and 40% sand), whereas in grazed pasture and crop land streams, substrates were by finer and comprised about clay 40% and sand 30%.

Sampling methods

Each stream was sampled for a range of physical and chemical parameters, fine particulate organic matter (FPOM), coarse particulate organic matter (CPOM), algae and benthic invertebrates. At each site a representative reach at least 10 m long and containing a riffle/run/pool sequence was selected. Physico-chemical factors measured on site were temperature, pH, specific conductivity at 25^{o}C (using a portable 4-star Orion pH/conductivity meter), and dissolved oxygen (using a WTW oxygen meter). A filtered water sample (0.75 µm pore size Whatman glass microfiber filters 25mm diameter disks) was also collected. Water samples (100 ml) were frozen and later brought to New Zealand where they were analysed for nitrate (Nitrate-N) using automated cadmium reduction, flow injection analyser method and dissolved reactive phosphate (DRP) using the molybdenum blue colorimetric method (R.J. Hill Laboratories Ltd, Hamilton, New Zealand). Minimum detectable levels were 0.002 g/m^3 (Nitrate-N) and 0.02g/m^3 (DPR). Unfortunately due to transport and preservation issues nutrient analyses were not considered reliable and have not been included in these results. Water clarity was measured with a secchi disk (20 cm diameter). Measurements were taken in the same manner by the same observer between 10 am and 2 pm local time following methods described by Lind (1979) and Cole (1994).

In the field up to 50 substrate particles were randomly selected and allocated to substrate size classes and a substrate index was then calculated following the method of Jowet and Richardson (1990). This substrate index (SI) was calculated using the formula;

Substrate Index = 0.08% bedrock + 0.07% boulder + 0.06% cobble + 0.05% pebble + 0.04% gravel + 0.03% sand and silt.

Mean width and depth were measured with a steel meter rule and measuring tape. Mean surface velocity was estimated using a floating object, which was allowed to float along a run, riffle and pool. The time taken to drift a measured distance was recorded.

Measurements were repeated three times and the average of the three readings taken to calculate velocity [v = t/d (v = velocity, t = time in s^{-1} and d = distance in cm)]. Channel stability was also evaluated at each site using the method of Pfankuch (1975).

Several riparian and human activity values were also assessed at each stream. They include the % riparian zone in pasture and forest estimated visually along each sampled reach, the presence or absence of livestock (primarily cattle) in the streams, and the degree of crop and human washing that occurred. Harvested maize is actively washed in streams turning them a milky colour.

Benthic invertebrates were collected in both qualitative and quantitative samples. At all reaches quantitative data were collected by taking five Surber samples (0.09 m^2, 500 μm mesh) from riffles. In order to get a more extensive species list, I also took a single qualitative, composite kick net sample (mesh 500 μm) from a range of run, riffle and pool habitats in each stream. Where they occurred, leaf packs, wood jams, and moss were included in the kick-net samples.

Benthic invertebrate samples were preserved in the field in 70% ethanol and were transported to New Zealand for laboratory processing. In the laboratory they were washed through a 500 μm mesh sieve, sorted, and identified to the lowest taxonomic level practicable (often family, sometimes genus). Morphologically different taxa within a family were classified separately (i.e., Leptophlebidae sp. A). Because the taxonomy of Nigerian aquatic invertebrates is poorly known, we used a combination of keys by Merritt and Cummins (1996), Yule *et al.* (2009) and Blakely *et al*. (2010), as well as numerous internet sources.

Algae and moss samples were obtained by scraping three randomly selected particles (50 mm^2 each) using a wire brush and washing the composite slurry into pottles. These samples were later filtered using a syringe and filter paper (Whatman glass microfiber filters 0.75 μm pore size, 50 mm diameter disks) and weighed in the laboratory to (0.01 mg). Suspended fine particulate organic matter (FPOM) samples were obtained by placing a 60 μm mesh net in the stream for 20 minutes. FPOM was transferred to a bottle in the field, and later filtered, oven dried (45^oC) and weighed in the laboratory to 0.01 mg. Coarse particulate organic matter (CPOM) was obtained from the Surber samples. CPOM was oven dried and ashed at 450^oC for three hours to calculate ash free dry mass (AFDM).

Data analysis

Principal component analysis (PCA) was used to examine differences in physico-chemical variables among streams. Ten variables were included (water temperature, pH, specific conductivity, dissolved oxygen (mg/L), water clarity, current velocity, wetted width, %

dissolved oxygen, substrate index and Pfankuch stability). PCA was run in PC-ORD using the correlation option which puts variables on an equal footing with each other (PC-ORD Version 4.01; McCune and Mefford 1999). Differences in physico-chemical and invertebrate variables for streams in the different land use type's were analysed with ANOVA. In all analyses streams were used as replicates and plots of residuals versus fit and normality plots were used to test for normality and homoscedasticity of data. Where assumptions of normality and homoscedasticity were not met response variables were log transformed (x + 1) (Zar, 1999). Benthic invertebrate diversity was calculated using Margalef's Index (Clifford and Stephenson, 1975). This is a measure of species diversity (or more strictly richness) calculated from the total number of species present and the total number of individuals. The higher the index, the greater the diversity. Simpson's index (Simpson, 1949) was also calculated to measure species evenness; communities dominated by a few taxa having higher index score, and are reported as Simpson's Reciprocal Index (1/D). Invertebrate community composition was compared using Detrended Correspondence analysis (DCA) run on PC-ORD (McCune and Mefford, 1999) and DCA scores were correlated with physico-chemical data using a Pearson's correlation coefficient. Non-metric multidimensional scaling (NMDS) was used to visualise the distribution of macroinvertebrate communities in ordination space. The analysis was based on quantitative data for the full list of taxa identified (Appendix 2), most of which are effectively morphospecies although few could be identified beyond family with confidence. Chironomidae were separated into subfamilies (Tanypodinae and Chironominae) and two tribes within the Chironominae, (Tanytarsini and Chironomini). The Bray-Curtis distance measure was used for the NMDS. ANOSIM was then used to examine whether significant differences occurred between groups of sites in four landuse categories (continuous forest, forest fragments, crop and pasture, and plantations). Finally SIMPER was run to assess which taxa were responsible for difference found between groups. All three analyses were run in the Freeware programme PAST (Hammer *et al.*, 2001).

Results

Physico-chemical variables

Many of the physico-chemical variables measured were significantly different between continuous forest, forest fragments, plantations and crop-pasture streams. Water temperatures were significantly higher in the crops and pasture streams than in continuous forested streams (means 25°C and 16°C, respectively) (Table 1), and there was a gradient of decreasing mean water temperatures between crops, plantations, forest fragments and continuous forests. All

streams had near circum-neutral pH and although statistically significantly differences were found (Table 1) they were unlikely to be of ecological importance. However, dissolved oxygen levels were also significantly lower in crop and plantation streams (means 36% and 46%, respectively) compared to forest fragment and continuous forest streams (means of 68% and 77%, respectively). Conversely, conductivity was highest in plantation streams, and lowest in crop and pasture streams, with forest fragment and continuous forest streams having intermediate conductivities. Water clarity and velocities were similar across all stream categories, while forested streams were slightly wider than crop and plantation streams. Bed substrate was finer in crop and plantation streams (dominated by sand and clay) compared to both forested stream types. Continuous forested and forest fragment streams were more stable (Pfankuch score) than pasture and plantation streams (Table 1).

The PCA of environmental variables indicated that PC1 explained only 18.6% of the variance and PC2 15.3%. The continuous forest and forest fragment sites were clustered together towards the left of axis one and were generally characterised by cooler temperatures, higher pH and dissolved oxygen concentration, larger substrata, faster current and clearer water (Fig. 2).

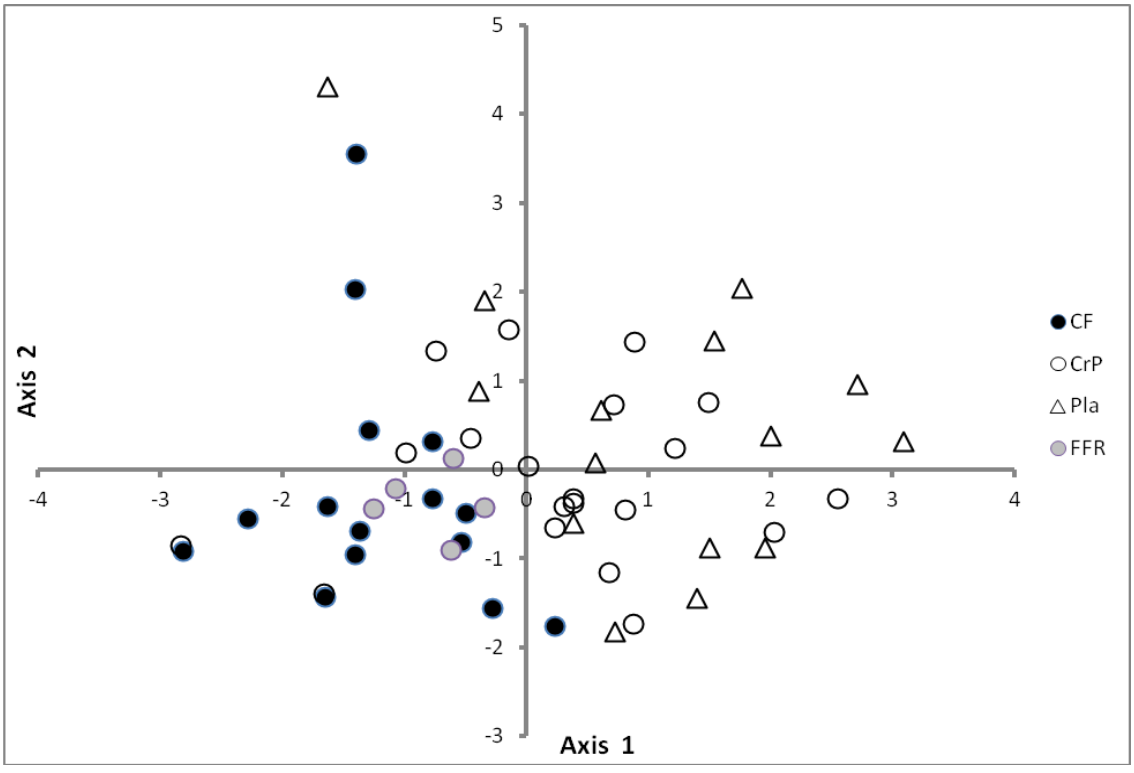


Figure 2: Principal component analysis (PCA) of physico-chemical variables among streams flowing through crops and pasture (CrP), Plantation (Pla), Forest fragment (FFR) and continuous forest (CF).

Organic matter

Organic matter samples of moss, algae, FPOM and CPOM did not show statistically significant differences between land uses. Surprisingly, similar quantities of algae and FPOM were found in pasture and forested streams, while on average CPOM biomass was highest in the continuous forest streams and lower in the crops and pasture streams (Table 2).

Table 1: Mean (± SE) and range for physico-chemical parameters of 55 study streams sampled between October 2009 and March 2010 on Mambilla Plateau, south east Nigeria (Streams sampled; Crops and pasture N = 20, Plantation N = 15, Forest fragments N = 5 and Continuous forest N = 15. Statistical values are for one way ANOVA. * Indicate significant difference ($P < 0.05$).

	Crops	**Range**	**Plantation**	**Range**	**F. frag.**	**Range**	**C. forest**	**Range**	**F-stat**	**P-values**
Temperature ^{o}C	25 (0.5)	20–27	21 (0.4)	17–24	18 (0.4)	15–22	16 (0.1)	13–19	3.25	0.02*
pH	6.4 (0.1)	6–8	6.3 (0.1)	5–8	7.2 (0.1)	7–7.4	7.2 (0.1)	6.4-8	3.91	0.01*
%DO	36 (1.0)	25–46	46 (1.1)	19–70	68 (1.0)	57–75	77 (0.8)	68–80	7.23	≤0.001*
Conductivity (μS_{25}/cm)	140 (2.4)	36–283	219 (11.0)	117–536	161 (6.0)	132–165	159(6.2)	31–280	5.32	≤0.001*
Clarity (m)	0.41(1.3)	0.2–1.0	0.38 (0.4)	0.2–0.7	0.54 (0.1)	0.2–0.5	0.8 (0.3))	0.3–0.7	0.75	0.52
Velocity (m/s^{-1})	1.0 (0.3)	0.1–0.26	0.6 (0.1)	0.1–0.26	0.6 (0.1)	0.2–0.26	0.3 (0.03)	0.2–0.26	2.41	0.07
Wetted width (m)	5.4 (0.1)	2–6	5.2 (0.3)	2–6	7.0 (0.4)	6–7	7.0 (0.2)	7–8	3.91	0.01*
Substrate index	4.3 (0.1)	3–6	5.3 (0.2)	3–7	5.3 (0.1)	5–7	7.0 (2.4)	7–8	8.18	0.001*
Pfankuch index	93 (3.0)	60–108	95(4.0)	70–108	70 (1.1)	65–78	55 (2.0)	35–68	9.16	0.001*

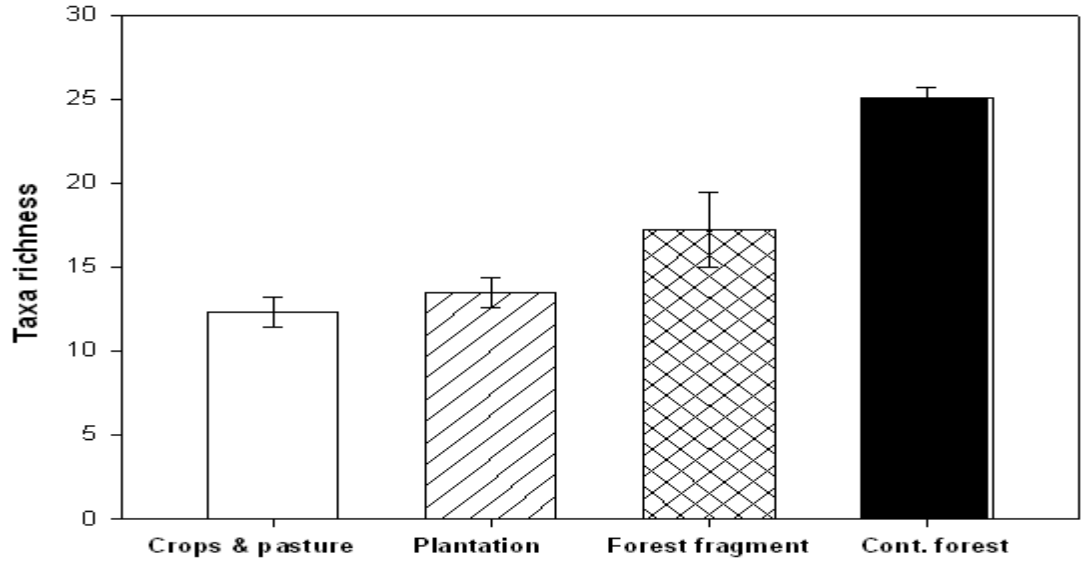
Table 2: Mean (± SE) and range of organic biomass collected from streams flowing through the four land use types. (Streams sampled; Crops and pasture N = 20, Plantation N = 15, Forest fragments N = 5 and Continuous forest N = 15. Statistical values are for one way ANOVA. * Indicate significant difference ($P < 0.05$).

	Crops	**Range**	**Plantation**	**Range**	**F. Frag.**	**Range**	**C. Forest**	**Range**	**F-stat**	**P-value**
Moss (DW g.m²)	0.08 (0.3)	0.01-0.1	0.1 (0.3)	0.01-0.6	0.02 (0.0)	0.01-0.03	0.02 (0.0)	0.01-0.03	0.88	0.45
Algae (DW g.m²)	0.04 (0.0)	0.01-0.07	0.03 (0.0)	0.01-0.09	0.04 (0.0)	0.01-0.07	0.07 (0.03)	0.006-0.5	0.78	0.5
FPOM DW (g/L)	0.08 (0.02)	0.01-0.2	0.06 (0.1)	0.01-0.1	0.02 (0.0)	0.004-0.06	0.02 (0.0)	0.005-0.06	2.05	0.11
CPOM (DW g.m²)	2 (0.4)	0.8-8.0	2 (0.1)	0.6-2.5	3 (0.6)	0.6-14	4 (0.3)	1.0-6.0	1.32	0.27

Invertebrate metrics and community composition

A total of 78 taxa in 11 orders were collected from 55 streams (Appendix 2). Of these a total of 64 taxa were found in continuous forest, 51 in forest fragments, 50 in plantations and 54 in crops and pasture. Mean taxonomic richness was significantly higher in the continuously forested streams compared to the forest fragment, plantation and crop and pasture streams (Fig. 3). After combining the kick-net and surber sampler data the highest individual stream taxonomic richness of 39 was recorded in a riparian forest fragment streams, whereas only 7 taxa were found in four streams; one in grassland, one in grazed pasture, one in a banana plantation and one in a Eucalypt plantation. Invertebrate densities were also higher in both continuously forested and forest fragment stream than in crop and plantation streams, with mean density in continuous forest streams reaching 260 individuals m^{-2} (Fig. 3). Pollution sensitive taxa, (i.e., Ephemeroptera, Plecoptera and Trichoptera EPT) varied across the four land uses, with the highest number of EPT taxa being nine at a continuously forested site where they comprised 27% of the community (Table 3).

A)



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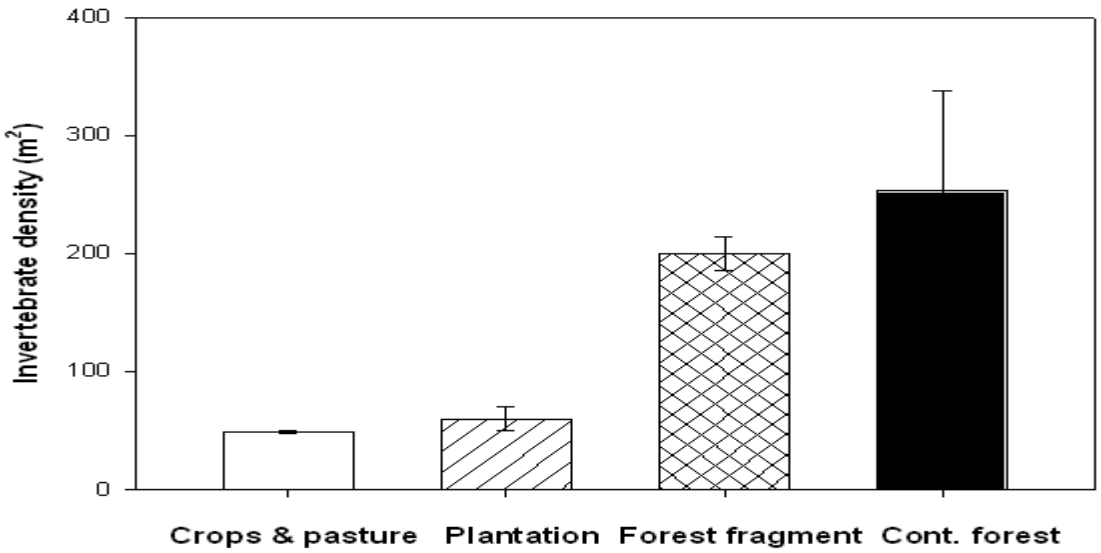
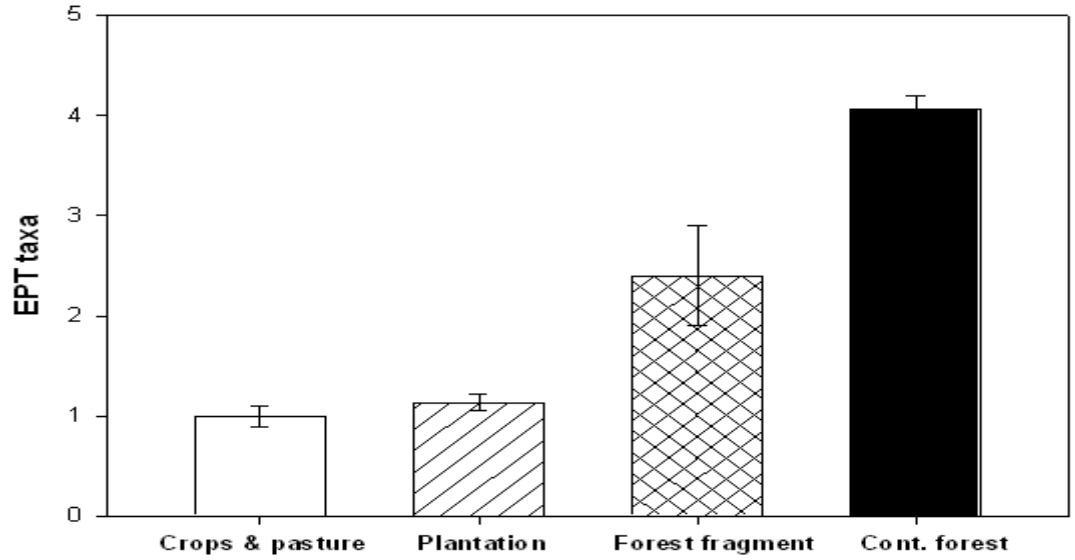


Figure 3: Mean (1±SE) benthic invertebrates sampled in streams flowing through four land uses between October 2009 and March 2010 on Mambilla Plateau (A) mean invertebrate taxonomic richness (based on combine kick-net and surber samples) and (B) invertebrate density (based on surber samples). (Crop and pasture n = 20, plantation n = 15 forest fragments = 5 and continuous forest = 15). ANOVA results in Table 3.

A)



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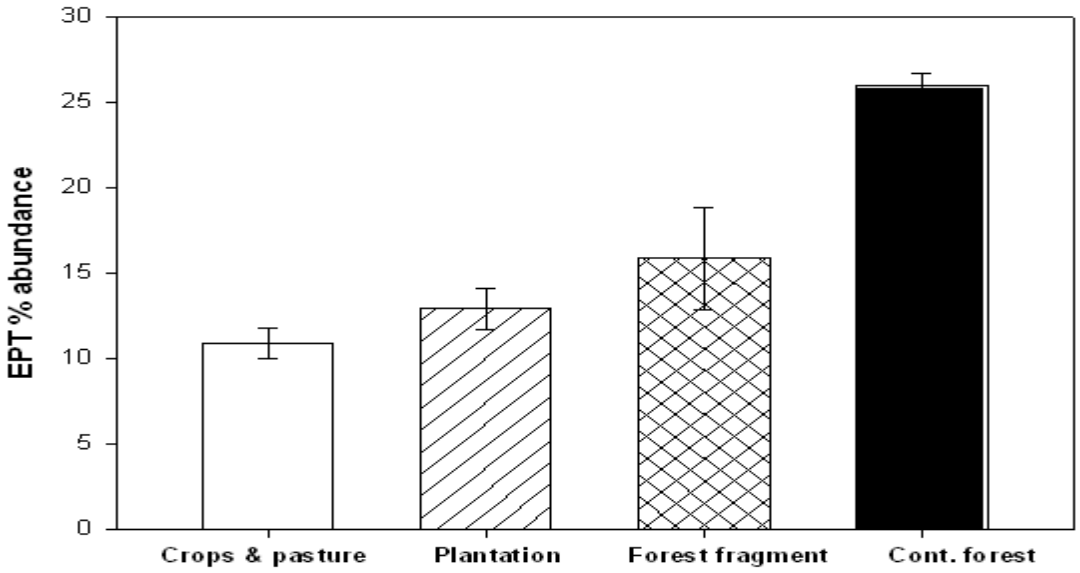
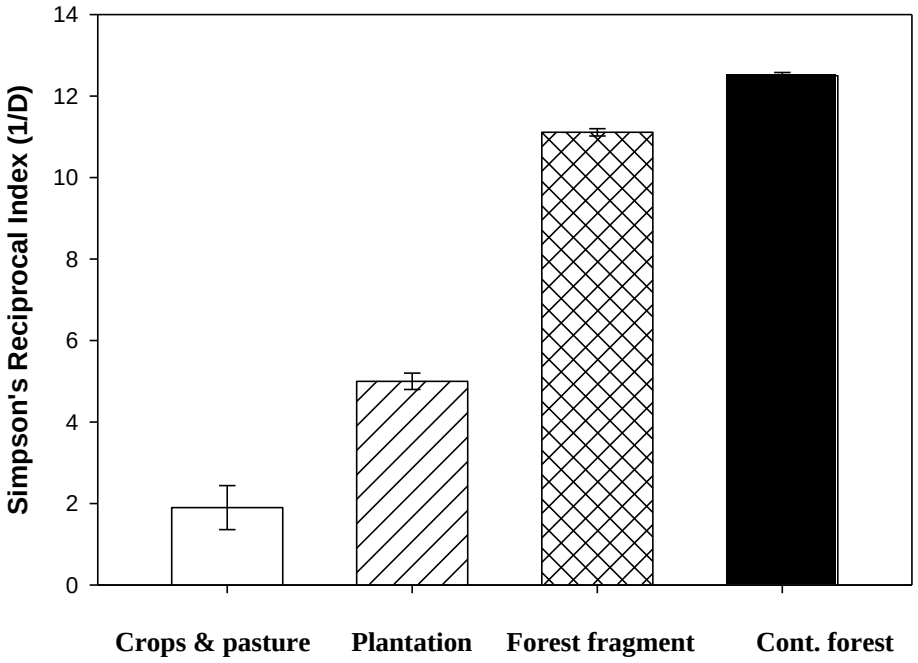


Figure 4: Mean (1±SE) Pollution sensitive taxa, mayflies, stoneflies and caddisflies (i.e., EPT) collected in four different land use between October 2009 and March 2010 (A) EPT taxa (based on combined kick-net and surber samples) and (B) EPT % abundance (based on surber samples). Mean (± SE) ANOVA results in Table 3.

A)



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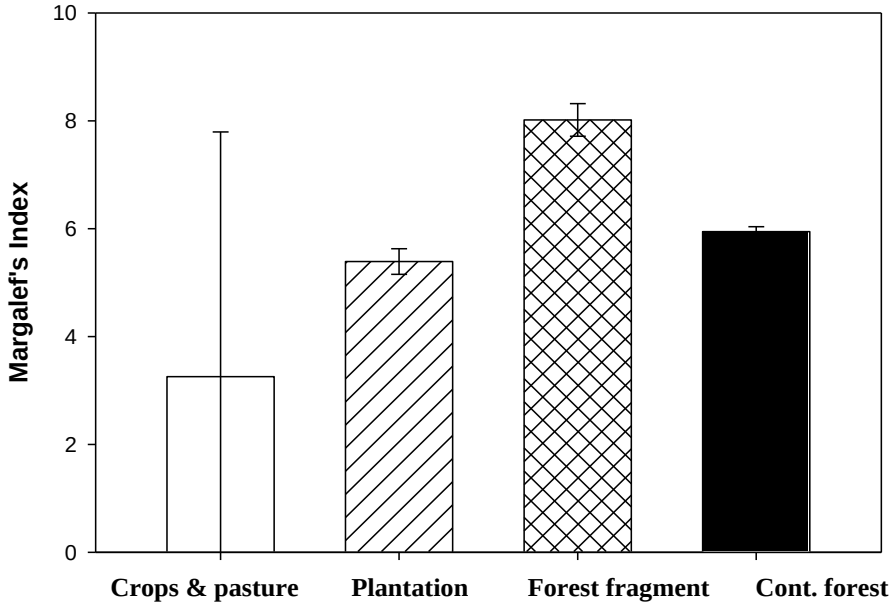

Figure 5: Mean (1±SE) Simpson's and (B) Margalef's diversity indices for benthic invertebrates collected from streams in four land uses on Mambilla Plateau between October 2009 and March 2010. ANOVA results in Table 3.

Table 3: Mean (± SE) and range for ANOVA of streams flowing through four land use types (crops and pasture n = 20, Plantations n = 15, forest fragments (F. Frag.) n = 5 and continuous forest (C. Forest) n = 15) Taxa richness, invertebrate density, EPT taxa, EPT percent abundance, Simpson's Reciprocal Index and Margalef's Index. * Indicate significant difference ($P < 0.05$) ANOVA.

	Crops	**Range**	**Plantations**	**Range**	**F. frag.**	**Range**	**C. forest**	**Range**	**F-stat**	**P-value**
Taxa richness	8.0 (1.2)	1–18	12 (3.4)	3–7	17 (1.0)	6–20	19 (0.9)	5–25	4.007	0.001**
Density (m^2)	1.0 (0.1)	0.1–17	1.1 (0.1)	0.7–1.7	1.4 (0.1)	0.8–2	2.0 (0.1)	1.2–2	4.139	0.01*
EPT taxa	2.0 (0.4)	1–6	1.1 (0.2)	1–4	3.0 (0.2)	3–6	4.0 (0.4)	3–7	7.449	0.001**
EPT %	1.0 (0.1)	0.3–1.3	1.4 (0.1)	0.4–1	0.4 (0.1)	0.1–0.7	1.1 (0.1)	0.4–0.7	5.247	0.002**
Simpson's Index	1.2 (0.1)	1–2.2	1.3 (0.1)	1–3	2.1 (0.1)	2–3	2.1 (0.1)	1–3	6.537	0.001**
Margalef's Index	3.2 (1.0)	2–7	5.3 (0.8)	0.3–12	8.0 (0.3)	7–10	6.0 (0.3)	3–7	3.440	0.02*

A number of taxa were absent or rarely found in streams associated with some land uses (Table 4). For example, although continuous forested streams had diverse communities that included up to six families of mayflies (i.e., Baetidae, Caenidae, Heptagenidae, Leptophlebiidae, Oligoneuriidae and Polymitarcidae), several of these families were absent or rarely occured in the other three land uses. Similarly, the only stoneflies collected (Perlidae) were largely limited to forested streams (Table 4). A total of nine of caddisfly families were collected: Hydropsychidae, Polycentropodidae, Lepidostomatidae, Glossosomatidae, Leptoceridae, Limnephilidae, Philopotamidae, Sericostomatidae and Psychomyiidae. Of these Limnephilidae were infrequently collected and not found at all in continuous forest and forest fragment streams, while Glossosomatidae and Sericostomatidae were rarely collected. Several dipteran families occurred in continuous forest but not in the other land uses, whereas a number of hemiptera taxa (i.e., Naucoridae, Notonectidae and Corixidae were generally absent from forested streams (Table 4).

Table 4: Taxa which were absent (*) or rarely occurred in Surber and kick-net samples for all streams from each of the four land use categories.

Crops and pasture	Plantation	Forest fragments	Continuous forest
Polymitarcidae*	Polymitarcidae*	Polymitarcidae*	Zygoptera
Heptagenidae*	Leptophlebiidae	Leptophlebiidae	Limnephilidae*
Caenidae	Caenidae	Caenidae	Naucoridae*
Perlidae	Baetidae	Baetidae	*Belostoma**
Sericostomatidae*	Heptagenidae*	Heptagenidae*	Notonectidae*
Glossosomatidae*	Perlidae*	Limnephilidae*	Corixidae*
Psephenidae*	Sericostomatidae*	Sericostomatidae*	
Empididae	Glossosomatidae*	Glossosomatidae*	
Muscidae*	Psephenidae*	Psephenidae*	
Arthericidae*	Empididae*	Empididae*	
Ostracoda*	Muscidae*	Muscidae*	
	Arthericidae*	Arthericidae*	
	Ostracoda*	Naucoridae	
		Notonectidae*	
		Corixidae*	

Several taxa were ubiquitous and occurred regardless of land use. These included Chironomidae and the two molluscs *Melanoides tuberculatus* and *Bulinus globosus* (Table 5). Gomphidae (Odonata) also occurred in most streams, while several mayfly families

(particularly the Leptophlebiiidae, Baetidae and Caenidae) occurred in most continuous forested streams. Brachyuran crabs were in streams in differing land uses but were most commonly in continuous forest with leaf and woody debris present (Table 5).

Table 5: Percentage (%) occurrence of taxa in streams of differing land use. Only taxa which occurred at greater than 50% of streams in each land use are shown.

	Crops and pasture n = 20	Plantation n = 15	Forest fragments n = 5	Continuous forest n = 20
Gomphidae	70	53	-	60
Leptophlebiidae	-	-	-	100
Baetidae	-	-	-	100
Caenidae	-	-	-	86
Oligoneuridae	-	-	66	60
Leptoceridae	50	-	-	-
Hydropsychidae	60	-	-	60
Lepidostomotidae	-	-	-	73
Hydrophilidae	-	60	-	-
Dytiscidae	55	-	-	-
Elmidae	-	-	-	60
Tanypodinae	50	-	-	87
Other Chironomidae	90	93	100	100
Melanoides	88	86	100	100
Bulinus	60	100	100	66
Brachyura	-	-	-	60

Macroinvertebrate quantitative data were used to perform non metric multidimentional scaling (NMDS) followed by analysis of similarity (ANOSIM) and similarity of percentages (SIMPER). NMDS separated most of the continuous forest sites from all other groups of sites on axis one (Fig 7). ANOSIM indicated that the communities at continuous forest sites differed significantly from those in all three groups (forest fragments, crops, plantations), but communities in crop and plantation streams did not differ significantly from each other (Table 6). SIMPER showed that the three most important taxa distinguishing groups were

Chironomini sp. A and the two gastropods, *Bulinus* and *Melanoides*. Chironomini made the highest contribution to dissimilarity among all groups and were most abundant in continuous forest and crop streams. *Bulinus* and *Melanoides* were most abundant in crop and plantation streams and Ostracoda were abundant only in forest fragment streams (Appendix 2).

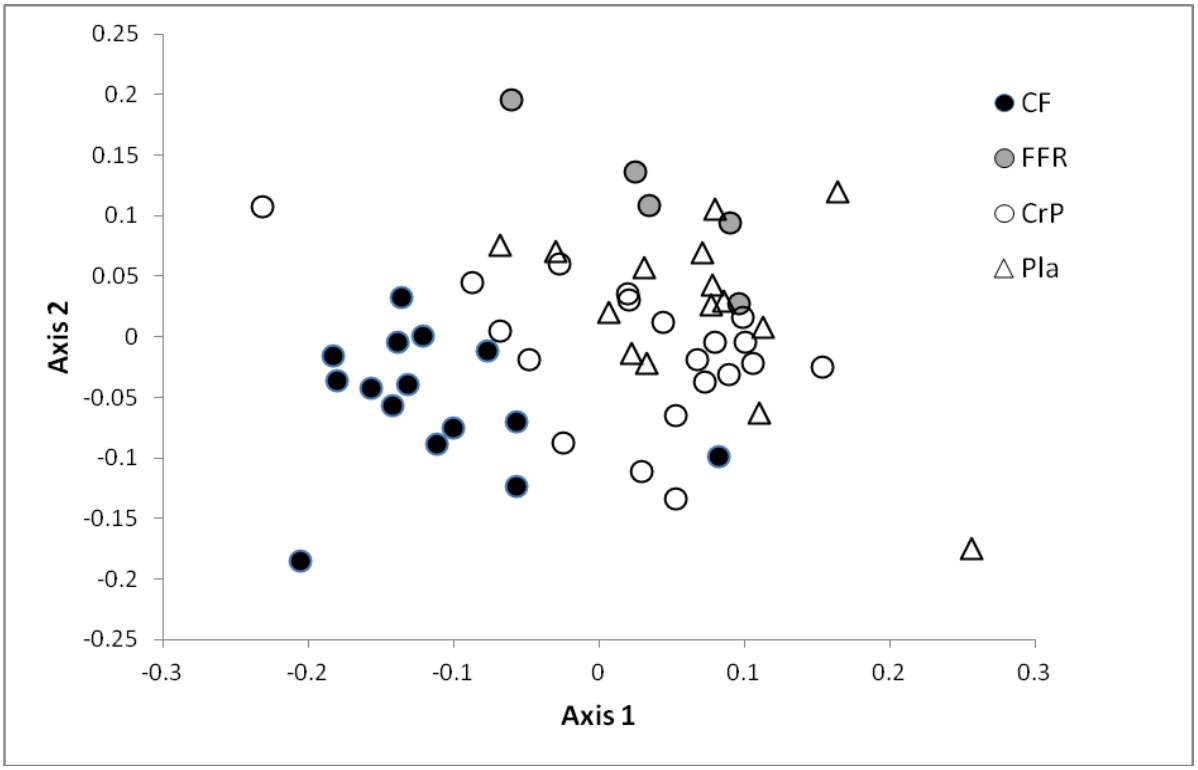

Figure 7: NMDS ordination using macroinvertebrate quantitative data folowed by ANOSIM and SIMPER of streams flowing through crops and pasture, plantation, forest fragments and continuous forest on Mambilla Plateau. Land use categories were (CrP) crops and pasture, (Pla) Plantation, (FFR) forest fragment and (CF) continuous forest.

Table 6: Significance values (uncorrected P values) among the 4 groups of streams. Significant < 0.05 = *.

	Continuous forest	Forest fragments	Crop & pasture	Plantation
Continuous forest		0.0002*	0.0001*	0.0001*
Forest fragments			0.0257*	0.0692
Crop & pasture				0.2086

Results of invertebrate DCA analysis were the same as that of the NMDS (not shown) and were used to examine correlations between invertebrate DCA scores and physico-chemical parameters are shown in Table 7. Axis one scores were significantly positively correlated with % pasture in the riparian zone, moss biomass and elevation are significantly negatively

correlated with % forest in the riparian zone, whereas moss biomass and elevation were significantly negatively correlated with % forest in the riparian zone, mean surface velocity, turbidity, substrate index and %dissolved oxygen (Table 7). Axis 2 was positively correlated with only two variables; the degree of crop washing occurring in the stream and elevation.

Table 7: Pearson's Correlation's with invertebrate DCA Axis 1 and Axis 2 against physico-chemical parameters from 55 streams. Bold indicates significant to $P < 0.05$.

	Axis 1	Axis 2
Axis 1	1	-
Axis 2	0.104505	1
Livestock	0.027087	-0.0835
Washing	0.107857	**0.24875**
Substrate Index	**-0.2342**	-0.18134
Channel Stability	-0.01324	-0.08892
Temperature	0.064241	0.000525
pH	-0.13481	0.091708
Conductivity	0.166341	-0.10654
Dissolved oxygen (%)	**-0.22383**	-0.15917
Dissolved oxygen (mg/L)	-0.16367	-0.11078
Water clarity	**-0.24234**	-0.06191
Velocity (m. s^{-2})	**-0.31341**	-0.05114
Moss (g m^2)	**0.227884**	-0.068974
Algae (g m^2)	-0.10191	-0.07338
FPOM (g m^2)	-0.01502	0.025743
CPOM(g m^2)	0.031435	0.021241
Inorganic sediment	0.179404	-0.02497
Elevation (m)	**0.241441**	**0.223595**
% forest	**-0.30676**	-0.13779
% pasture	**0.306758**	0.13779

Discussion

Globally the effects of intensive land use activities have been shown to have negative impacts on benthic diversity and to alter stream communities (Allan *et al.*, 1997). Although little is known about tropical highland streams we expected they would respond in such a manner. My four contrasting land uses; continuous tropical montane rainforest, forest fragments, plantation and crops-pasture had significant effects on stream benthic communities. My data suggest that the intensification of land use associated with plantations, crops and pasture has resulted in a marked decline in diversity and modification of the invertebrate communities in small streams on the Mambilla Plateau. In particular the most sensitive taxa (Ephemeroptera, Plecoptera, and Trichoptera) were more diverse in forest

streams than at the cultivated sites with EPT taxa richness being higher in continuous tropical rainforest and riparian forest fragments and lowest in a stream with a cabbage crop. However, not all crop and pasture streams had highly impacted communities, they were highly variable and in some cases were similar to those in continuous forest streams and in other cases similar to plantation stream communities. Some crop and pasture streams had wider riparian buffer zones (e.g., up to 15 m wide) that appeared to help project them, whereas others had crops planted right to the margins of the streams. Although I did not measure riparian zone width it was apparent that riparian planting, livestock access and farming intensity all played a role in impacting benthic communities.

The higher diversity in forested streams is consistent with findings by other workers elsewhere. For example, in a study into the effects of historic deforestation on stream faunas of Banks Peninsula New Zealand, Harding (2003) found that taxonomic richness was significantly greater in forested streams than agricultural streams, particularly for Ephemeroptera, Plecoptera and Trichoptera taxa. Furthermore, distributions of two regionally-endemic hydrobiosid caddisflies *Costachorema peninsulae* and *Edpercivalia banksiensis* were restricted to forest fragments. Two other Banks Peninsula endemics, the stonefly *Zelandobius wardi* and the caddisfly *Hydrobiosis styx* were rarely collected but seemed to be restricted to headwater sites in forest. In contrast, the blephariceridid *Neocurupira chiltoni* was widely distributed in streams, regardless of land cover, and its abundances appeared to be unrelated to site location within a catchment. Harding (2003) concluded that a number of species may also have been lost in other parts of New Zealand because of past deforestation, and that remnant forested habitats may be vital to the conservation and preservation of regionally endemic species. As the taxonomy of my Nigerian streams fauna is poorly understood I was not able to determine whether any of my taxa were regionally endemic. However, given the high diversity of plant and other animal species in West Africa it is possible that a number of regionally endemic invertebrates may occur on the Mambilla Plateau.

Iwata *et al.* (2003) investigated the impacts of past riparian deforestation associated with slash-and-burn agriculture on stream habitats and communities in Borneo, East Malaysia, by comparing streams running through primary forests with those in secondary forests that had been deforested 9–20 years previously. Their findings showed distinctive differences in the depositional character of stream habitats; secondary-forest reaches had finer substrates, more eroded banks, and larger areas of depositional habitat and cover than did primary-forest reaches. Although their findings suggest that such altered habitats are

recovering toward a predisturbance state with redevelopment of the secondary forests, effects of habitat alteration on stream communities were still evident. Habitat alteration (i.e., sedimentation) lowered the abundance and/or diversity of benthic assemblages (periphyton, aquatic insects, shrimps, crabs, and benthic fishes) but nektonic fishes were less affected. The results obtained by Iwata *et al.* (2003) also indicated that habitat alteration benefited a few benthic taxa such as caenid mayflies and two shrimps (*Macrobrachium trompii* and *Caridina nilotica peninsularis*). Overall, effects were detrimental, however, leading to a reduction in biodiversity of the stream communities. The authors concluded that slash-and-burn agriculture, which alters vegetation and soil conditions more intensively than logging, caused long-term degradation of stream communities (Iwata *et al.*, 2003).

My findings are also broadly similar to those of Victor and Ogbeibu (1995) who investigated the benthic communities of fourth order agricultural streams flowing through farmland in southern Nigeria. They found 55 benthic taxa of which Chironomidae and Baetidae were the most common families. In my four land uses Chironomidae frequently occurred in all land uses, whereas Baetidae occurred in all my continuous forest streams but infrequently in the other land uses. Victor and Ogbeibu (1995) also recorded differences in taxonomic richness, diversity and evenness between their sites, with diversity being much higher at the less disturbed sites than in downstream sections perturbed by agricultural and urban activities.

In a study of the macroinvertebrates of water bodies in southern Nigeria spanning rainforest and derived savannah ecozones, Olumokoro and Ezemonye (2007) found 55 taxa, belonging to 13 major groups. Abundance of the major taxonomic groups varied considerably among the 20 water bodies with Chironomidae well represented and dominant in 11 of them. The rarest species were gastropods (Mollusca), and is in contrast with my findings that two gastropods *Melanoides tuberculatus* and *Bulinus globosus* were common across all my land uses. Overall abundance in the southern Nigeria study was highest in lowland forest (97 taxa at Okomu River) and lowest in savannah (5 taxa at Avielle River). Olumokoro and Ezemonye (2007) concluded that human impacts on invertebrate biodiversity included changes in fauna distribution patterns.

The most abundant insect orders found on the Mambilla Plateau were Ephemeroptera, Diptera, Coleoptera and Trichoptera, especially the families Oligoneuriidae (*Elassoneuria* sp.), Chironomidae (*Chironomus* spp. & Chironomini sp. A), Elmidae and Hydropsychidae. A similar assemblage of families has been reported for other tropical stream assemblages (Boyero and Bailey, 2001; Jacobson *et al.*, 2008) on Coiba Island, Panama where the above

listed families (except Hydropsychidae but including Psephenidae) were most abundant and widely distributed.

The continuous forest and forest fragment streams were rich in several ephemeropteran taxa and the single plecopteran, most of which were not collected in plantation crops and pasture streams. This situation is consistent with the findings of Olumokoro & Ezemonye (2007) and Quinn & Hickey (1990), who reported that pollution sensitive mayflies and stoneflies were either absent or less abundant in streams within agriculturally developed catchments. The ANOSIM showed difference between continuous forest and the other three land use categories (crops and pasture, plantation and forest fragments). SIMPER also showed that the most indicative taxon was Chironomini species A.

Although chironomids are not necessarily limited by physical habitat conditions, and therefore can occur in many streams (Awachie, 1981), they are known to replace other invertebrate taxa in Nigerian water bodies polluted by agricultural and domestic activities (Ogbeibu and Egborge, 1995). The low number of taxa and high abundance of Chironomidae found at our cultivated sites is in accord with findings reported by Corbi and Trivinho-Strixino (2008), in a study which investigated the influence of sugar cane cultivation on the macroinvertebrate communities of 11 streams under different land uses in Jacaré-Guaçu River Basin, State of São Paulo, Brazil. They found 96 macroinvertebrate taxa, of which 54 were Chironomidae. The Brazilian streams located in the areas of sugar cane culture and pasture had low number of taxa and a high occurrence of Chironomidae (an average of 78% all benthic invertebrates). In contrast, streams located in areas with riparian vegetation had a richer aquatic fauna and a lower proportion of Chironomidae (60% of total macroinvertebrates) (Corbi and Trivinho-Strixino, 2008).

The mayfly families Baetidae, Caenidae and Heptageniidae were rarely collected outside continuous forest and forest fragment streams on the Mambilla Plateau, whereas the family Oligoneuriidae (represented by a single genus *Elassoneuria*) also occured, infrequently in pasture streams. This latter mayfly possesses thoracic and lateral abdominal gills indicating a potentially strong adaptation to stressed dissolved oxygen conditions. Human activities such as deforestation are a primary threat to mayfly biodiversity, conservation and pollution (Rosemberg and Resh, 1993; Benstead *et al.*, 2003; Dudgeon *et al.*, 2006). For example, Benstead *et al.* (2003) in a study of biodiversity threats in Madagascan freshwaters, found fish and macroinvertebrate species were limited to streams and rivers draining primary forest and forest fragment. My findings were consistent with this scenario.

Larvae belonging to damselflies (families uncertain) were found mostly in crop and pasture streams on the Plateau. They were associated with macrophytes, which were absent from forested streams. Other studies also indicate that stream-dwelling odonate larvae are often associated with macrophytes (Ravera, 2001; Ruggiero *et al.*, 2003; Carchimini *et al.*, 2004; Aromoro *et al.*, 2007b; Popoola and Otalekor, 2011).

Mohammed et al. (2013) conducted a mathematical analysis using the maximum sum algorithm method to determine environmental variables affecting the Nigerian highland stream benthic communities. The algorithm successfully detected variables such as temperature, dissolved oxygen levels and substrate index as having effects on the number of macroinvertebrates in streams in the different land use types. They concluded that low temperatures, higher dissolved oxygen levels and larger substrates size in the forested streams favoured higher numbers of macroinvertebrates. In contrast lower numbers of macroinvertebrates were recorded in crops and pasture land use types where temperatures were higher, dissolved oxygen levels very low and substrate size much finer (mostly mud and sand). In my study species diversity was highest in streams draining continuous montane rain forest probably because they had high substrate heterogeneity and greater canopy cover, which provided shading (Arimoro *et al.*, 2012). In contrast, streams with crops such as maize and cabbage were opened-canopied and, had abundant decomposing crop plant matter on their beds. The presence of this plant matter almost certainly resulted in lower dissolved oxygen concentration (at least at night) and increased the biochemical oxygen demand (BOD). As on the Mambilla Plateau low species diversity and abundant chironomids were found in the Ogunpa River, Nigeria where BOD was also high due to the presence of decomposing crops and sewage (Ogidiaka *et al.*, 2012). Similarly, Corbikleine and Trvinho-Strixino (2012) found that forested streams in Brazil had higher invertebrate richness and diversity of EPT taxa than banana plantation streams, consistent with our findings that banana plantation streams had very low diversity (3–6 taxa) and few EPT. On the Mambilla Plateau crops such as cabbage, tea, maize and bananas are often washed and partially processed in nearby streams by local farmers, practices that can also be expected to result in a lowering of water and habitat quality. Overgrazing and bush fires also lead to soil erosion on the Mambilla Plateau and sediment accumulation in streams.

The standing stocks of wood, leaves and other coarse organic materials were not different between streams of different land cover (forest, forest fragment, plantations and crops and pasture). In summary, streams in the four land use types show progressive modification. Thus there was progressive change of invertebrate diversity and community

composition moving from forest, forest fragments and plantation to the crops and pasture streams. NMDS, ANOSIM and SIMPER analyses of invertebrate assemblages in streams associated with each of the four land use types (continuous forest, forest fragment, plantation and crops and pasture) indicated a more or less sequential change of faunal composition along this "land use gradient".

In conclusion, results of my study indicate that intensive land use activities have strongly reduced the diversity and altered the composition of benthic invertebrate communities on the Mambilla Plateau. Continued intensification of agricultural activities and lack of recognition of the impact of poor farm practices both on the Plateau and elsewhere in Nigeria will continue to cause degradation of watercourse, unless practices such as the planting of trees and shrubs as riparian strips are implemented to help protect the stream ecosystems. Of special concern are the fates of several species that are poorly known to science and currently seem to be restricted to streams in continuous forest and riparian forest fragments that are under threat from agricultural development. Further investigation on the implications of these tropical land use activities is required because of the fragile nature of these ecosystems.

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Chapter four

Riparian land use and the relationship between invertebrate communities and litter decomposition in a tropical highland stream

Introduction

The relationship between biodiversity and ecosystem processes has potentially critical implication for understanding and management of ecosystems, but despite years of intense debate its importance remains controversial (Tilman *et al.*, 1997; Cardinale *et al*., 2000). In tropical streams, the relationship is poorly understood and is further complicated by the role of floods and flashy discharge and by interactions with terrestrial catchment processes (Jonson and Malmqvist, 2003; Covich *et al*., 2004; Wright and Covich, 2005). Understanding these relationships and interactions becomes increasingly important as lotic ecosystems throughout the world undergo rapid land use changes that affect not only the structure of their biological communities (Stone and Wallace, 2002), but also ecosystem processes (Freeman *et al*., 2007).

Leaf litter breakdown is an important ecosystem process (Dudgeon, 1994; Gessner and Chauvet, 2002), particularly in streams where litter inputs represent a significant source of energy and nutrients (Wallace *et al.*, 1997; Abelho, 2001; Graca, 2001). In such streams changes in riparian vegetation, e.g., reduced litter inputs, increased light and temperature fluctuations, have been shown to result in marked changes in the benthos (Wallace *et al.*, 1997; Encalada *et al.*, 2010).

Numerous studies have demonstrated the importance of insect consumers in the process of organic matter breakdown in temperate streams e.g., Wallace and Benke (1984) and Thompson and Townsend (2000). In temperate stream ecosystems, leaf shredding is often carried out principally by aquatic insects larvae (e.g., Trichoptera, Plecoptera and Diptera), and also Amphipoda (Crustacea). However, in tropical streams, shredding insects may be rare or absent (Cheshire *et al*., 2005; Yule *et al.*, 2009), whereas other taxonomic groups (notably large crustaceans) can fill this functional role (Crowl *et al.*, 2001; Wantzen and Wagner, 2006b). For example, the freshwater shrimp *Xiphocaris elongata* is the dominant shredder of leaf litter in Puerto Rican streams (Crowl *et al.*, 2001; March *et al.*, 2001). However, this pattern is not consistent, for example, Jacobsen *et al.* (2008) stated that highland tropical streams in South America support a rich shredder fauna composed of taxa typical of temperate streams (e.g., limnephilid caddisflies and tipulids) as well as taxa more

characteristic of tropical streams (e.g., calamoceratid and leptocerid caddisflies and decapod crustaceans). All these groups were present in Ecuadorian Páramo streams, but they were not abundant, presumably because of the absence of riparian vegetation at altitudes above about 400 m above sea level (Jacobson *et al.*, 2008).

Yule *et al.* (2009) reported that the species of shredders in Malaysian streams differed between lowland and the upland areas. Lowland shredders included prosobranch snails, crabs, calamoceratids caddisflies, and semi-aquatic cockroaches, whereas shredders in upland streams were mainly stoneflies, limnephilid and lepidostomatids caddisflies and tipulids. Yule *et al*. (2009) suggested that the occurrence of different shredder species might be influenced by the characteristics of available leaves. For example dipterocarp trees in Malaysian lowlands typically have tough, leathery leaves, whereas vegetation in upland regions comprises more deciduous species with relatively palatable leaves similar to those in many North American and European forests. In contrast the Australian tropics are dominated by the same evergreen species of trees regardless of upland or lowland status, and their leaves are processed by similar invertebrate species (Yule *et al.*, 2009).

Gradients in shredder richness and abundance have been reported in both temperate and tropical regions. Both Winterbourn *et al.* (1981) and Thompson and Townsend (2000) suggested that temperate New Zealand was depauperate in shredders, as are tropical Micronesian islands (Benstead *et al*., 2009), Hawaii (Larned, 2000) and parts of Indonesia and New Guinea (Dudgeon 1994; 2006). However, high shredder abundance has been recorded in some tropical streams in Australia Queensland (Cheshire *et al*., 2005) and peninsular Malaysia (Yule *et al.*, 2009). In contrast shredders richness and abundance can be very high in many temperate streams in North America (Webster et al., 1999) and Europe (Dobson *et al*., 2002).

This observed scarcity of insects shredders in tropical streams, has led to the conclusion that rapid litter processing in the tropics must be brought about by high rates of microbial activity associated with high water temperatures (e.g., Irons *et al.*, 1994; Ramirez and Pringle 1998; Dudgeon and Wu 1999; Dobson *et al.*, 2002b; Benstead *et al.*, 2009). However, this may not be the case in all tropical streams, especially those where other shredding consumers are common, including fishes (Rosemond *et al.*, 2002), shrimps and crabs (March *et al.*, 2001; Dobson, 2004) and prosobranch snails (Li and Dudgeon, 2008a; Yule *et al.*, 2009). In the tropics the correct assignment of taxa into functional feeding groups (FFGs) has been an additional challenge (Cummins, 1973). Incorrect assignment of taxa has been demonstrated for various insects' taxa, especially mayflies (Yule and Pearson, 1996; Dobson *et al.*, 2002a,;

Cheshire *et al.* 2005). FFG classification is further complicated by the fact that some taxa can shift their major feeding mode in response to food availability, changes in riparian shading and life history stage (Li and Dudgeon, 2008a). For these reasons, no substitute exists for careful analysis of feeding habits of tropical taxa (e.g., Cheshire *et al.*, 2005; Li and Dudgeon, 2008a).

While the effects of land use on benthic invertebrates have been studied in temperate systems, their potential effects on litter processing have rarely been assessed in the tropics (McKie *et al.*, 2009; Encalada *et al.*, 2010), and to my knowledge no studies of this type have been published on Nigerian streams.

The objective of the present study was to compare leaf litter breakdown in streams draining catchments with differing land uses (tropical montane rain forest, tea plantations and maize fields) on the Mambilla Plateau, and to determine the nature of the benthic invertebrate communities found in leaf packs. I predicted that differences in shading and temperature would markedly influence leaf breakdown rates, but also as crabs and tipulids also occur in these systems, invertebrate shredders may play an important role which differs between land uses.

Methods

Study area

The study was conducted in the tropical montane region of the Mambilla Plateau, in the south east corner of Taraba State, Nigeria (11º- 6º E, 6º- 7º N). All streams sampled were near the Ngel-Nyaki Forest Reserve (Fig. 1) in the head waters of the Donga River. The Plateau is at an altitude of approximately 1500 m a.s.l. and the rainy season last for an average of 250 days, from late March to the end of October. In contrast from November to mid-March, the region is relatively dry and may be affected by the harmatan (a dry cold north - south wind) between December and January. Mean annual rainfall exceeds 1780 mm, peaking in June and July, however, due to the high elevation of the Plateau the daily mean temperature rarely exceeds 30ºC. During this study mean air temperature was about 24^{o}C.

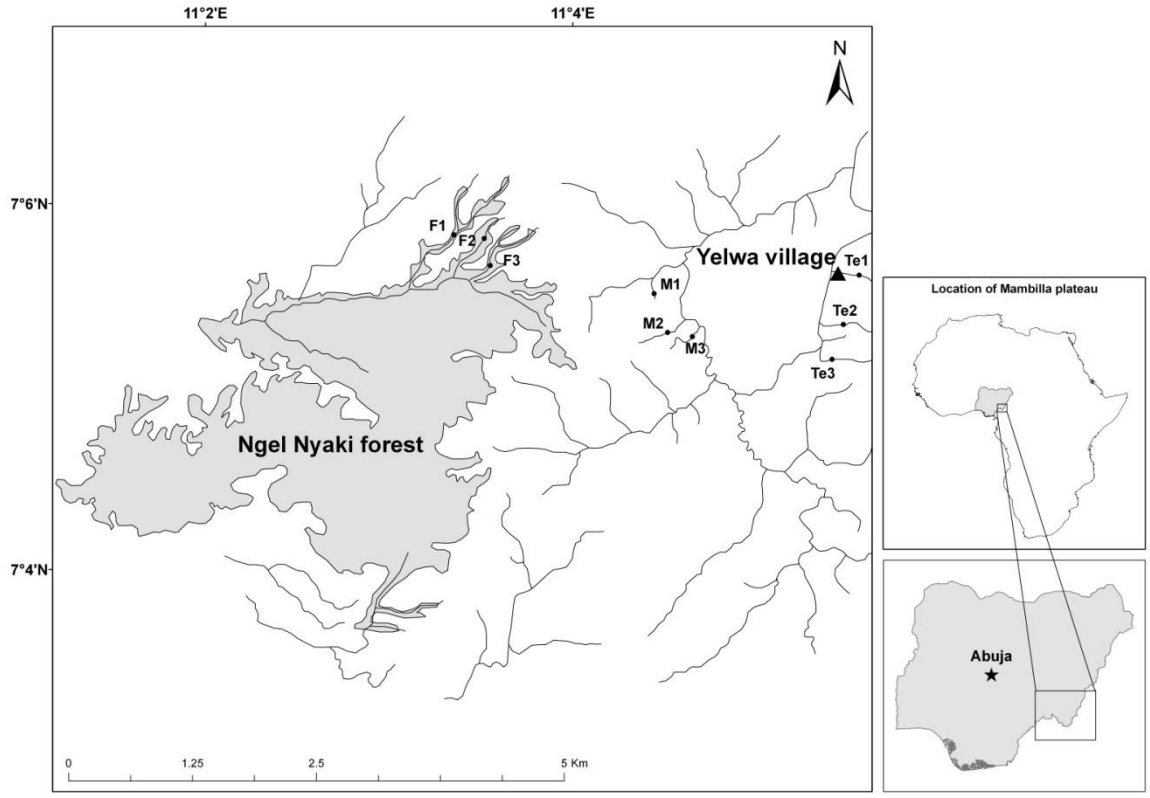

Figure 1: Location of nine study streams near Ngel-Nyaki Forest Reserve, Mambilla Plateau, Taraba State, Nigeria. Site abbreviation: F = continuos forest, Te = tea plantations, M = maize fields.

My study was carried out in nine second order, headwater streams, three in Ngel-Nyaki tropical rainforest, three in tea plantations and three in maize fields. Several tree species were present at both forest and agricultural sites, but the most common in both was *Syzygium guineense* (Myrtaceae). This tree species is native to the wooded savannahs and tropical forest of Africa (Noudogbessi *et al.*, 2008). Because it was common in the area it was chosen for the litter breakdown experiment. In hindsight this may not have been a good choice because it was slow to decompose.

Physico-chemical measurements and leaf collection

A range of physico-chemical parameters and characteristics of the riparian vegetation were measured at the forest, tea plantation, and maize sites.

Physico-chemical parameters measured in situ including temperature, pH, specific conductivity at 25^{o}C (using a 4-star Orion pH/conductivity portable meter), and dissolved oxygen (using WTW oxygen meter). A filtered 100 ml water sample (0.75 µm pore Whatman

glass microfiber filters, 25 mm diameter disks) was also collected for subsequent nutrient analysis. Unfortunately these samples were not able to be adequately preserved and transported and have been omitted from the analysis. Water clarity was measured with a secchi disk (20 cm diameter). Measurements were taken in the same manner by the same observer between 10 am and 2 pm local time following methods described by Lind (1979) and Cole (1994). In the field up to 50 substrate particles were randomly selected and allocated to substrate size classes and a substrate index calculated following the method of Jowett and Richardson (1990). The substrate index (SI) was calculated using the formula;

Substrate Index = 0.08% bedrock + 0.07% boulder + 0.06% cobble + 0.05% pebble + 0.04% gravel + 0.03% sand and silts.

Mean stream widths and depths were measured with a steel metre rule and measuring tape. Mean surface current velocity was estimated using a floating object, which was allowed to float along a run, riffle and pool. The time taken to drift a measured distance was recorded. Measurements were repeated three times and the average reading used to calculate velocity [v = t/d (v = velocity, t = time in s^{-1} and d = distance in cm)]. Channel stability was evaluated at each site using the method of Pfankuch (1975). Percentages of forest and pasture were estimated visually along a 20 metres reach and 5 metres back from the stream at each site.

Syzygium guineense leaves were collected in litter-fall traps constructed from polythene plastic sheets measuring 2m x 2m (Fig. 2) at Ngel-Nyaki forest. Two traps were placed in the forest 1 m above the ground, using ropes attached to trees. Litter was recovered from each trap after one week and dried for 24 hours at 30^{o}C.

Leaf breakdown

A total of 62 leaf bags were constructed with 54 of them deployed in the stream. Each mesh bag was cut from "an onion bag", was 14 cm long x 16 cm wide and had a pore size of 30 mm which allowed entrance of all macroinvertebrates to the bags. Six grams (± 0.1 g) of air dried *Syzygium guineense* leave were placed in each bag (Fig. 2).

At the start of the experiment (21st February 2011) 54 of the 62 leaf bags were placed in the nine streams, three sets of two bags in each stream. Leaf bags were anchored to the stream substratum at each site using logs and were dispersed along the stream channel in similar conditions of water velocity and depth (Fig. 2d). The other eight leaf bags were taken to the field and returned on the same day to the laboratory for weighting to check potential mass loss of leaf material during transport. Two replicate bags of each treatment were collected after two weeks, four weeks and six weeks, respectively, to assess litter breakdown

(% mass remaining). All samples were frozen following collection, bags were placed in individual plastic zip-lock bags containing stream water and transported to the laboratory in an icebox as described in Hauer and Lamberti (2007).

Figure 2: (A) *Syzygium guineense* leaves being air dried (B) dry leaves on digital weighing scale, (C) onion mesh bags (mesh size 30 mm) filled with 6 gm dry weight leaves and (D) leaf mesh bags being placed in a stream.

In the laboratory, leaf packs were thawed and washed through a 500 µm-mesh sieve to remove fine debris sediments and benthic invertebrates. Invertebrates retained on the sieve were sorted, removed, identified to the lowest taxonomic level possible and counted. The keys of Merritt and Cummins (1996), Yule *et al*. (2009) and Blakely *et al.* (2010) were used for identification.

Leaves were tested for toughness with a penetrometer (Feeny, 1970; Quinn *et al.*, 2000). Penetrance is a relative measure of leaf toughness, and is defined as the weight required to force a blunt rod through a leaf (Young *et al.* 1994). Fifteen measurements were made on leaves randomly drawn from each leaf pack, leaf veins being avoided. Penetrance pressure (PEN, kPa) was calculated after Quinn *et al*. (2000) using the formula 9.807 M / 0.785 (where 9.807 N is gravitational force, M is the applied mass needed to pierce the leaf and 0.785 mm^2 is the area of the tip of the rod). The weight of the penetrometer stand was 22 g and thus the penetrance pressure was 275 kPa. When the rod penetrated the leaf without

applying any additional weight half the penetrance value was recorded (Quinn *et al.*, 2000; Barnden and Harding, 2005). Young *et al.* (1994) suggested that freezing may alter leaf penetrance, but because all leaf packs received the same treatment this should have affected all leaves, equally.

When penetrance measurements had been completed all leaf pack material was oven dried at 56 ^{o}C for 48 h and weighed to the nearest 0.001 g. It was then ashed at 500^{o}C for 4 h and reweighed. Ash free dry mass (AFDM) was calculated by subtracting the mass of ash (in grams) from that of the dry matter (Benfield, 1998).

Data analysis

Differences in physico-chemical and invertebrate variables for forest, tea plantation and maize field streams were analysed by ANOVA. In all analyses streams were used as replicates and plots of residuals versus fit and normality plots were used to test for normality and homoscedasticity of data. Where assumptions of normality and homoscedasticity were not met response variables were log transformed (x + 1) (Zar, 1999).

The rate of leaf breakdown (-*k*/day) in each stream was modelled as a negative exponential function (Peterssen and Cummins, 1974) using the dry weight of the leaf packs:

$$- k \text{ day} = \log_e (\% R/ 100) / t$$

Where, % R = dry weight of leaf remaining after 42 days.

Cumulative degree-days were estimated by summing the averaged spot water temperatures (^{o}C) on each sampling occasion over each incubation period (i.e., the degree-days accumulated from day one to the retrieval date) in place of days (Benfield, 1998).

Overall differences in the composition of invertebrate assemblages in leaf bags taken from forest, tea plantation and maize fields were assessed using analysis of similarity (ANOSIM) (Bray-Curtis similarity calculated with quantitative data) (Clarke and Gorley, 2006). Diversity of the leaf bag invertebrate shredder assemblages were estimaated using Simpson's diversity index (Simpson, 1949).

The relationship between shredder density and decay rates was assessed using regression analysis. Repeated measures ANOVA was used to test the effects of stream type and time (weeks) on leaf toughness, the number of taxa in leaf packs, and the number of invertebrates per gram leaf pack. Mean values for each stream were used as replicates.

Results

Physico-chemical variables

Physico-chemical variables differed between forest, tea plantation and maize streams. However, not surprisingly percentage forest cover was greater in the forest than in the tea and maize streams (88% and 5% respectively) and water temperatures were significantly higher in the maize and tea plantation streams than in the forested streams (26°C and 16°C respectively) (Table 1). A number of other parameters were also significantly different for example the pH in all streams was circum-neutral but higher in forested streams and dissolved oxygen concentrations were significantly lower in maize and tea plantation streams compared to forested streams (51%, 49% and 79%, respectively) (Table 1). However, specific conductivity was significantly higher in tea plantation and forested streams than maize field streams (Table 1), for unknown reasons. Stream width differed across land uses, with maize streams being wider than those in the other land uses. Substrate was much finer in maize and tea plantation streams (i.e., gravel and sand) compared to forested streams, which had boulders and cobble substrates. Maize and tea plantation streams were more physically unstable than forested streams.

Table 1: Mean (± 1 SE) physico-chemical characteristics of streams sampled in March 2012, on the Mambilla Plateau Nigeria (n = 3 for each of maize, tea and continuous forest). Statistics are result of one way ANOVA. * indicate significant difference ($P < 0.05$).

Parameters	**Maize fields**	**Range**	**Tea plantation**	**Range**	**Cont. forest**	**Range**	**F-stat**	**P-value**
Chemical								
Temperature ^{o}C	26.3 (0.3)	25–27	21.7 (0.6)	21–23	16.6 (0.15)	16.3–16.8	3.25	0.02*
pH	6.3 (0.2)	6.0–6.6	6.6 (0.2)	6.3-6.8	7.1 (0.1)	6.8-7.3	3.91	0.01*
%DO	51.2 (0.3)	50–52	49.2 (1.5)	47.4–52.2	79.6 (4.7)	71.4–88	7.23	≤0.001*
Conductivity (μScm^{-1})	100 (16.6)	69-126	252 (62)	128-315	217 (17.5)	193–207	5.32	≤0.001*
Clarity (m)	0.3 (0.02)	0.3–0.4	0.5 (0.03)	0.4–0.5	0.7 (0.03)	0.8–0.9	4.33	0.02*
Physical								
Velocity ($m\ s^{-1}$)	0.19 (0.03)	0.13–0.23	0.20 (0.03)	0.4–0.24	0.83 (0.08)	0.66–0.97	40.93	≤0.001*
Wetted width (m)	6.1 (0.2)	5.7–6.7	3.6 (0.1)	3.4–4	4.8 (0.1)	4.5–5.2	28.71	≤0.001*
Substrate Index (SI)	3.1 (0.3)	2.5–3.5	4.3 (0.1)	4.1–4.6	7.3 (0.4)	6.5–8.2	39.87	≤0.001*
Channel stability	82.6 (3.7)	78–90	70.6 (4.3)	62–74	36.3 (0.8)	35–38	51.52	≤0.001*
%forest	34.6 (4.8)	25–40	37.6 (1.4)	35–40	72.3 (1.4)	70–75	47.52	≤0.001*
%pasture	61.6 (2.0)	55–70	30 (2.8)	25–35	24.3 (2.3)	20–28	36.55	≤0.001*

Leaf breakdown

During the first few days, leaf litter weight loss was probably rapid as significant amount of soluble compounds were leached from leaves into the streams (Nykvist, 1961a). After two weeks between 20 and 50% weight loss had occurred (Fig. 3a). However, between four and six weeks the rate of weight loss slowed in maize and tea plantation streams, although further reductions in weight were observed in forested streams. A comparison based on time showed after six weeks the overall leaf weight loss was similar across stream types (Fig. 3a) and not significantly different (One-way ANOVA; $F_{2,\ 24} = 0.525$; P = 0.597). However, by correcting weight loss using degree-days a different pattern emerged. Weight loss in forest streams was faster on that basis, and after 650 degree-days (dd) the remaining leaf mass in the forested streams dropped from 70 g to 30 g (Fig. 3b). In contrast, in tea plantation streams the rate of mass loss was slow and was only 45 g after 800 dd, whereas in maize field streams mass loss slower 55 g after 1000 dd (Fig. 3b). Breakdown rates (-*k*) from 0.001 - 0.0011 per day indicated that *Syzygium guineens* (Myrtaceae) had slow leaf breakdown rates according to Petersen and Cummins (1974), i.e., less than 0.005 day^{-1}. Leaf toughness did not differ among the three stream type (Table 2), however, there was a time effect indicating that leaf toughness declined over time in the stream (Fig. 2b). Furthermore, a significant land use by time interaction (Table 2) indicated that the rate of decline in leaf toughness differed among stream types (Table 2).

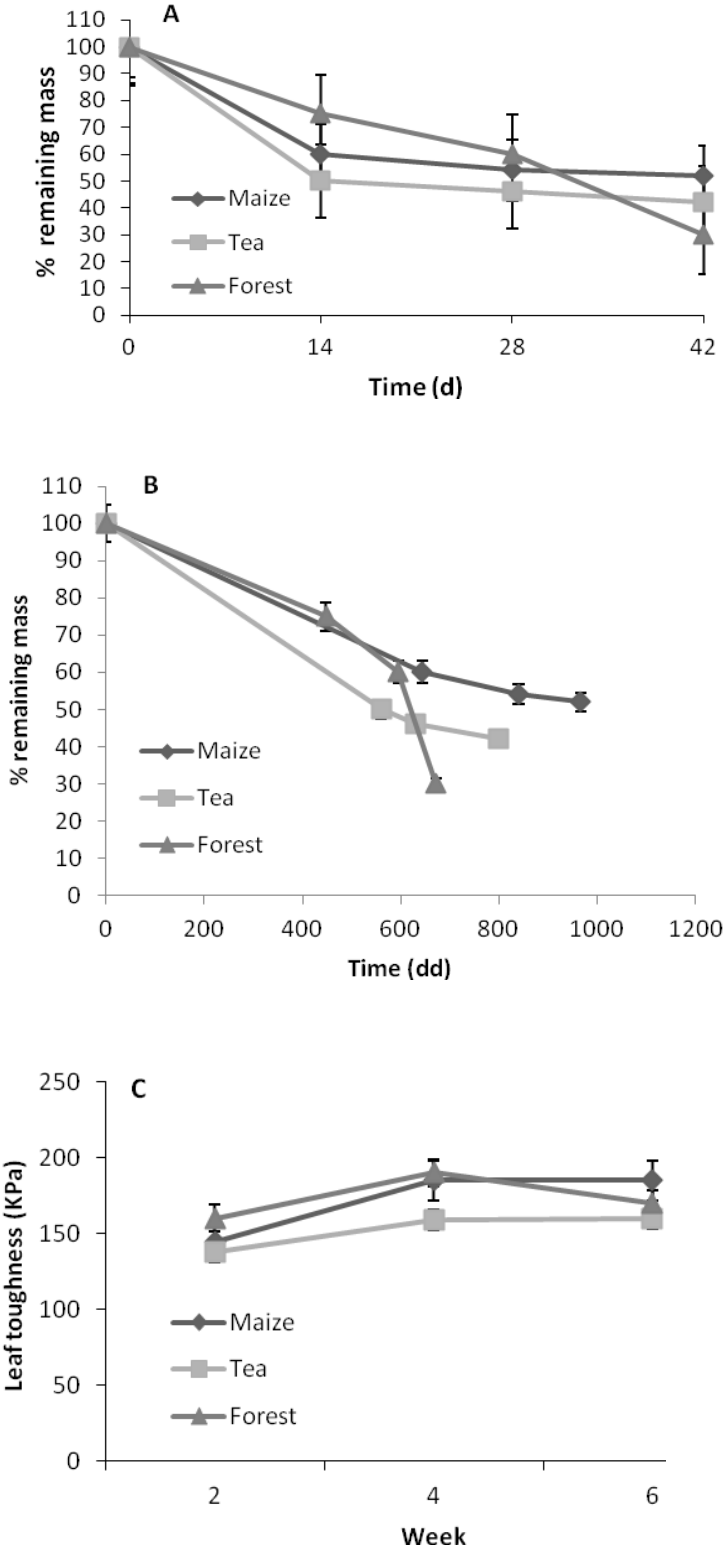

Figure 3: Mean (± 1 SE, n = 3) mass loss relative to time expressed as (A) days, (B) degree days and (C) changes in leaf toughness of *Syzygium guineense* leaves during the leaf-litter breakdown experiment in three types of streams over six weeks in the dry season (between February and April, 2011) on Mambilla Plateau Nigeria.

Benthic invertebrates

Number of invertebrate taxa in leaf bags differed significantly between forest, tea plantation and maize fields sites (ANOVA, $F_{2, 15} = 8.399$; $P = 0.003$). Taxonomic richness was significantly higher in forest (mean 30 per leaf pack) than tea (17) and maize (10) (Fig. 4a), and Simpson's diversity index showed that forested stream communities had higher evenness (0.10) than tea plantation streams (0.05) and maize field streams (0.02) respectively. Invertebrate densities were higher in leaf packs from forested streams than tea plantation and maize streams (Fig. 4b) although variation among forested streams was high.

Surprisingly, taxon richness did not change significantly over the six weeks of the experiment. Shredders were collected in leaf bags from all land uses but few were found in bags from tea plantation and maize field streams (Fig. 3c, Table 2). Shredder taxa were significantly more abundant in forest than tea plantation and maize fields stream bags (ANOVA $F_{2, 6} = 10.919$, $p = 0.01$, Table 2, Fig. 4c). In contrast, predators and scrapers were significantly more abundant in maize field streams than in forest and tea plantation streams (Table 3, Fig. 5).

Table 2: Repeated-measure ANOVAs comparing leaf toughness and colonisation of packs by invertebrates across maize, tea and forested stream over six weeks. *F* values and significance shown, where * $P < 0.05$, *** $P < 0.001$, ns = not significant.

	Toughness	**No. of taxa**	**No. of invertebrates**	**No. of shredders**
Between subjects				
Land use	2.05 ^{ns}	2.64 ^{ns}	9.28 *	62.68 ***
Within subjects				
Time (Week)	9.45 *	4.37^{ns}	1.22 *	12.25*
Land use: time	4.60 *	1.65 ^{ns}	0.13 ^{ns}	0.19 ^{ns}

Table 3: Mean (± SE, n = 3) abundance of taxa in leaf packs in streams flowing through maize field, tea plantation and forest sampled between February and April 2011 on the Mambilla Plateau Nigeria. Functional feeding groups; P = predator, C = collector, Sh = shredder, Sc = scrapers and - = absent.

Taxa	Maize fields	Tea plantation	Forest	FFG
Odonata				
Gomphidae	4.7 (0.9)	3.0 (1.2)	3.0 (0.6)	P
Ephemeroptera				
Leptophlebiidae	-	-	1.0 (0.0)	C
Oligoneuriidae	-	-	2.7 (0.3)	C
Plecoptera				
Perlidae	-	-	2.0 (0.0)	P
Trichoptera				
Calamoceratidae (*Anisocentropus*)	-	-	15.0 (2.9)	Sh
Glossosomatidae	-	3.0 (0.2)	5.0 (2.0)	C
Hydropsychidae sp. A	-	-	10.3 (0.7)	C
Hydropsychidae sp. B	1.3 (0.3)	5.7 (1.9)	1.0 (0.0)	Sh
Lepidostomatidae	1.0 (0.1)	2.0 (0.0)	10.0 (1.5)	Sh
Leptoceridae sp. A	-	-	4.3 (0.9)	Sh
Leptoceridae sp. B	-	-	4.7 (2.0)	Sh
Polycentropodidae	-	2.0 (0.0)	3.3 (0.3)	C
Coleoptera				
Dysticidae sp. A	-	-	1.2 (2.0)	P
Dysticidae sp. B	-	1.5 (0.4)	2.0 (1.2)	P
Elmidae sp. C	2.0 (0.1)	1.2 (2.0)	-	C
Elmidae sp. A	1.0 (0.1)	-	3.3 (1.2)	C
Elmidae sp. B	1.0 (0.1)	2.0 (0.0)	3.5 (1.2)	C
Gyrinidae	4.0 (0.6)	3.0 (1.1)	-	P
Hydrophilidae	1.0 (0.0)	3.0 (0.2)	1.5 (0.4)	P
Ptylodactylidae	-	2.5 (0.4)	2.0 (0.0)	C
Scirtidae	-	-	3.0 (0.8)	CB
Diptera				
Empididae	-	2.0 (1.2)	1.3 (0.3)	CB
Tipulidae (*Limonia*)	-	-	5.7 (1.5)	Sh
Mucidae			3.3 (1.3)	C
Simulidae (*Simulium*)			5.7 (1.5)	C
Tipulidae spp.	3.3 (1.8)	2.7 (1.5)	20.7 (2.2)	Sh
Tipulidae (*Hexatoma*)	3.0 (1.5)	2.7 (1.2)	11.33 (2.4)	P
Hemiptera				
Notonectidae	3.0 (0.8)	-	1.0 (0.5)	P
Mollusca				
Melanoides tuberculatus	1.7 (0.3)	2.0 (0.8)	1.33 (0.9)	Sc
Crustacea				
Atyidae	-	-	2.0 (0.0)	C
Potamonautidae (Brachyura)	4.0 (0.6)	6.0 (0.6)	16.0 (4.2)	Sh
Total	31.0 (0.3)	44.3 (0.4)	146.46 (1.0)	

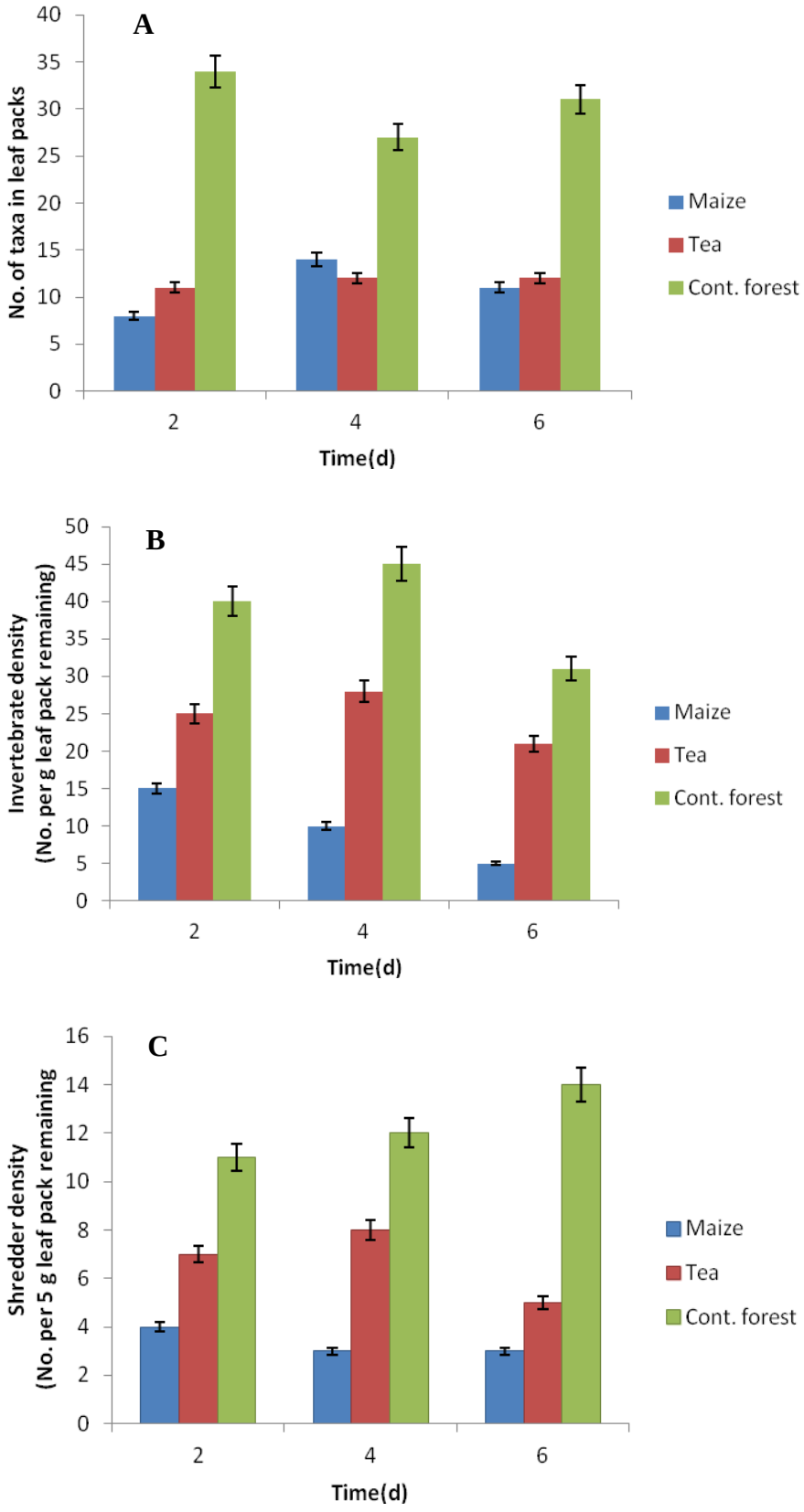

Figure 4: Mean (± 1 SE, n = 3) (A) taxonomic richness, (B) number of invertebrates and (C) number of shredders in leaf bags in the three streams types on three sampling occasions (between February and April, 2011) on the Mambilla plateau, Nigeria.

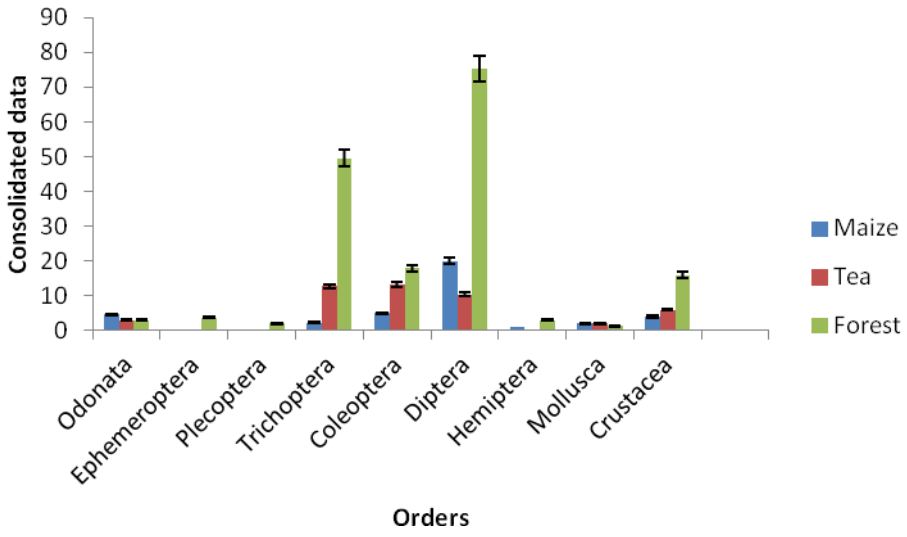

Figure 5: Mean (± SE, n = 3) consolidated data for the different macroinvertebrate orders in leaf packs in streams flowing through maize field, tea plantation and forest sampled between February and April 2011 on the Mambilla Plateau.

The most abundant invertebrate families represented in leaf bags taken from the forest streams were the Tipulidae (Diptera) and the caddis families Calamoceratidae (probably *Anisocentropus* sp.) and Lepidostomatidae, whereas in the tea plantation and maize streams, the dominant families were collector-scraper beetles Elmidae, caddis Hydropsychidae and Potamonautid crab (Table 3).

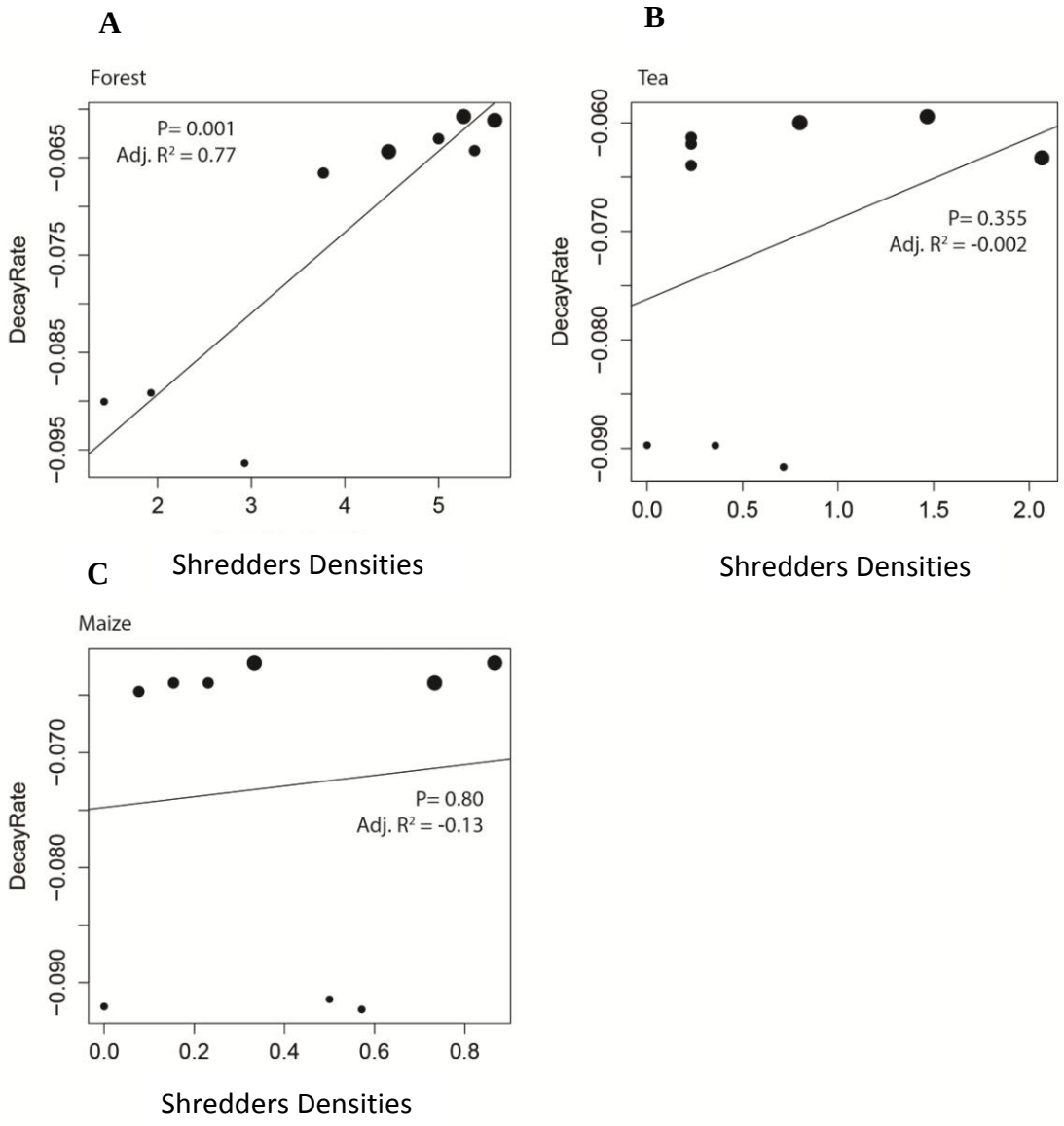

Figure 6: Regression of leaf decay rates against shredder densities in leaf packs (A) forest, (B) tea and (C) maize fields.

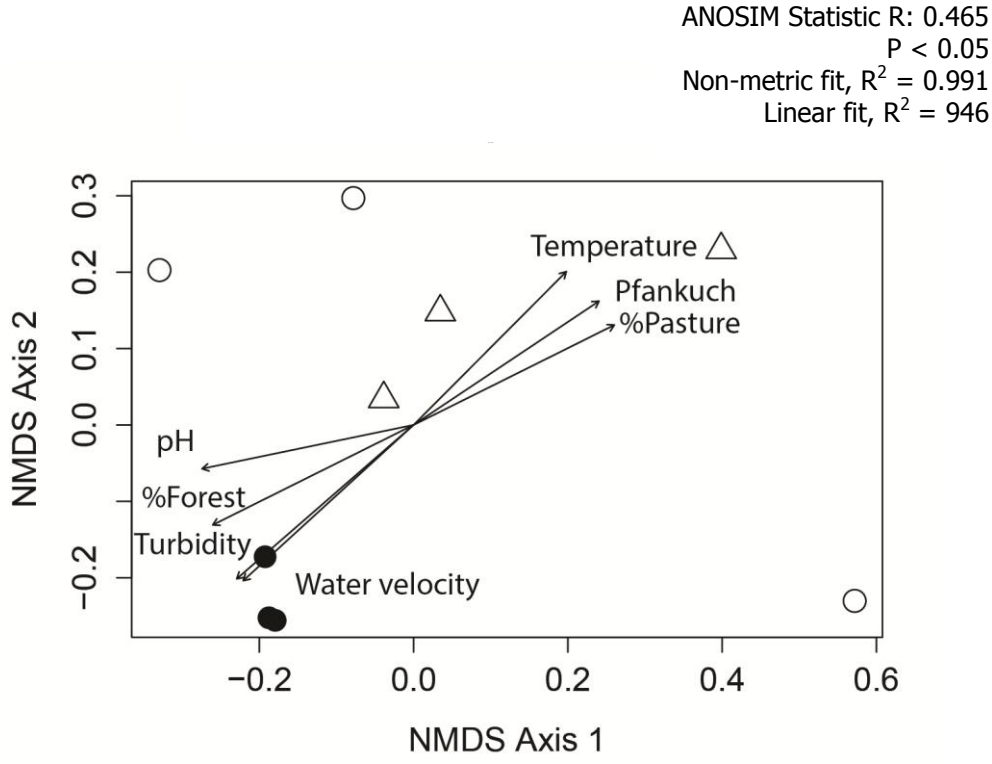

Figure 7: NMDS showing differences in invertebrate communities in leaf packs of the three land uses over time after six weeks. Land use categories were Forest ●, Tea ○, Maize △

The relationship between shredder density and decay rate was assessed by regression analysis. Forested streams showed a significant positive correlation between decay rate and macroinvertebrate density through time, indicating that shredders potentially influenced breakdown rates (Fig. 6a). In contrast, in tea plantation and maize field streams there was no significant correlation between decay rates and shredder density (Fig. 6b, c). Therefore, in plantations and maize streams shredders might not strongly influence the rate of decay. With higher water temperatures in the tea plantation and maize field streams it was possible that microorganisms had a greater role in mediating breakdown rates.

A non metric multidimentional scale (NMDS) used to visualise the distribution of macroinvertebrates in ordinate space followed by analysis of similarity (ANOSIM) was performed on quantitative invertebrate and physico-chemical data in order to test the differences between invertebrate communities in leaf packs of the three land uses over time. Water clarity (turbidity), pH, velocity and percent forest were the major environmental drivers of invertebrate communities in the forested streams. Whereas in the tea plantation and maize field streams warmer water temperature, poorer channel stability and higher percent

pasture were more strongly implicated for driving the macroinvertebrate communities (Fig. 7).

Discussion

The main objective of this study was to assess whether land uses (forest, tea plantation and maize field) had significant effects on the rate of litter decomposition. The degree day data indicated that leaf breakdown initially occured quickly although there was greater leaf breakdown in the forested streams. The rate of leaf breakdown (-*k*) in all my streams was slow relative to what has been reported in most tropical litter decay studies and, comparable to what was reported by Benstead *et al.*, (2009) for a Pacific island stream in Micronesia. Leaf toughness and the presence of defensive chemicals in leaves of *Syzygium guineense* may have been partially responsible for this (Noudogbessi *et al.*, 2008).

Factors that affect leaf decomposition processes in streams include the chemical composition of the leaf (Day, 1982), water quality and inorganic sediment deposition, physical abrasion and temperature (Suberkropp and Chauvet, 1997; Maamri *et al.*, 1997). For example, Manuel *et al.*, (2006), in a study of litter dynamics in deciduous forest stream in Central Portugal, reported decomposition rates increase with nitrogen contents of leaves, and decreased as the amount of chemical and physical defences of the leaves increased.

High water temperatures in tropical streams might be expected to result in fast litter processing due to high rates of microbial activity (Irons *et al.*, 1994; Dudgeon and Wu, 1999; Dobson *et al.*, 2002b). I found that tea and maize streams had higher temperatures than forested streams, but over the course of the experiment (6 weeks) breakdown rates were faster in forest than tea and maize, indicating a less important role of temperature in leaf break down. Some stream invertebrates use leaf litter as both a food source and as habitat and Dudgeon and Wu (1999) showed that palatable leaves (*Fiscus fistulosa*) attracted more invertebrates, and were processed faster than less palatable ones (*Castopsis fissa*). Leaves in general may be a more recalcitrant food source for shredding organisms in the tropics than in temperate regions because leaves of tropical trees are generally much richer in secondary compounds than are leaves from temperate trees (Boyero *et al.*, 2009; Dobson *et al.*, 2002b).

I observed that shredder density varied across the streams draining catchments with different land uses with my forested streams having much greater shredder densities. Thus, I expected faster weight loss in the forested streams, which I observed, initially. Regression

analysis of shredders against breakdown rates showed a strong relationship in forested streams, weaker in tea and virtually no relationship in maize streams. This variation in shredder density between the forested, tea plantation and maize field streams may have been a consequence of differences in abundance of leaf litter, dissolved oxygen concentration and substrates composition among the stream types. Some support for the importance of leaf litter availability as a variable influencing shredder density comes from a number of tropical African studies. For example Olomokoro and Okologume (2008) found that 38% of the 29 invertebrate species found in the Ogba River, Nigeria occured on gravel and 62% occured on leaf litter. In their study the dominant invertebrates were *Desmocaris tripinosa* (Crustacea: Decapoda), *Adenophlebiodes* sp. (Ephemeroptera) and *Clinotanypus maculata* (Diptera).

However, Dobson *et al.,* (2002) found that the number of individuals and the proportion of detritivores at Kenyan stream sites were equivalent to, or greater than those at European sites, although shredders were absent from the Kenyan streams. They concluded that tropical African streams were functionally different from those in temperate regions and suspected that either enhanced microbial activity replaced shredder processing of leaves at high temperatures, or that the low palatability of leaves in tropical streams deterred direct leaf feeding. The result of my leaf breakdown experiment suggests that breakdown was primarily due to shredding in forested streams (and to a lesser extends in the tea streams) but that microbial processing was more important in the maize streams.

In some tropical regions, the relative abundance of shredders is now known to be greater than previously thought. For example Cheshire *et al.* (2005) found an abundant and diverse shredder assemblage in streams of the Australian wet tropics where heterotrophic pathways based on allochthonous litter appeared to predominate. Yule *et al.* (2009) also suggested that some of the variation in shredder richness and abundance in tropical streams might reflect variation along altitudinal as well as latitudinal gradients.

I found potamonautid crabs (Crustacea: Decapoda) at all my sites, and in other tropical streams where crabs can be important leaf shredders (Covich 1998; Wantzen and Wagner, 2006) analyses of their gut contents indicated they fed to a large extend on leaves and wood (see Chapter 5). Strong linkages between shrimp assemblages and rates of detrital decay have been confirmed elsewhere (March *et al*., 2001). However, the roles of shrimps on the Mambilla Plateau remain to be determined. It is probable that larval tipulids to the subfamily Tipulinae were the most important insects feeding on leaves in the Mambilla Plateau stream. They were found in leaf bags and because they typically have a strongly alkaline anterior gut (pH 10.5–11.0) that enhances protein digestion (Barlocher and Porter, 1986; Graca and

Barlocher, 1998; Canhoto, 2001), they are likely to have the ability to feed on chemically well defended leaves such as those of *Syzigium guineense* (Noudogbessi *et al.*, 2008; Jayasinghe *et al.*, 2003).

The abundance of detrital feeding calamoceratids (*Anisocentropus*) collected from my forested streams was similar to that reported by Encalada *et al.* (2010) in a tropical montane forest stream in north-western Ecuador. Their most abundant calamoceratid, *Filloicus* sp., was the best predictor of the rate of litter decomposition suggesting it had a major role in leaf breakdown. Although Ogbogu (2006) found *Anisocentropus* larvae associated with leaves trapped by exposed roots of shade trees in another Nigerian stream. I was unable to confirm their role as an agent of leaf breakdown on the Mambilla Plateau. Several studies on the feeding biology of shredding caddisflies have reported faster growth rates on leaf species that either decompose more rapidly (i.e., have softer structural tissue, and/or greater nutrient concentrations) or that are preferred by shredders (Canhoto and Graca, 1996; Hutchens and Webster, 1997; Larned, 2000, Quinn *et al.*, 2000; Dudgeon and Chan, 2006; Bastian *et al.*, 2007). However, some aquatic detritivores have been shown to increase their feeding rates on low-quality leaf litter apparently to compensate for poor food quality (Anderson and Cummins, 1997; Friberg and Jacobsen, 1999; Li and Dudgeon, 2008a).

Significantly lower densities of invertebrates were found in leaf bags incubated in streams draining tea plantation and maize fields than in forest streams. The most abundant shredders colonizing bags at all sites were larvae of Tipulidae (Diptera) and Calamoceratidae (Trichoptera). However, the role of shredders in the tea and maize streams is less clear.

Finally, my NMDS analysis indicated that environmental, physical and water chemistry conditions may have also played some role in leaf breakdown in my three land uses. Some of these factors (e.g., %pasture/forest, temperature and channel stability) are related to land use. However, the role of pH and water velocity is less clear. Although pH and water velocity were significantly different between land uses, it seems less likely that they were ecologically significant.

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Chapter five

Food web structure in tropical highland stream ecosystems

Introduction

Food webs are being increasingly used by ecologists to demonstrate patterns of biodiversity and energy flow in ecosystems (Thompson *et al.*, 2012). A significant advantage of such an approach is that food webs can generate information on community structure, competition, nutrient dynamics, and cascading effects of predation which can be difficult to detect using other methods (Winemiller and Polis, 1996). Furthermore, food web studies have been used to measure the effects of disturbance on aquatic systems, for example McHugh *et al.*, (2010) showed that disturbance can have an important role in restructuring food-webs in streams.

In forest stream ecosystems, food webs are typically driven by allochthonous organic inputs, (often dominated by leaf litter), as their primary energy source (Kaushik and Hynes, 1971; Vannote *et al.*, 1980). Leaf litter is leached, colonized and decomposed by micro-organisms, and consumed by macroinvertebrate shredders (Dudgeon, 1982; Benfield, 1996; Gessner *et al.*, 1999). As a result leaves and wood are broken down into fine particulate organic matter (FPOM). FPOM also enter directly from the riparian zone and can be consumed by invertebrate collectors. Invertebrate shredders, grazers and collectors are the major primary consumers in forest streams, and serve as a link between basal carbon resources and the predatory invertebrates and vertebrates. The biomass of benthic algae in shaded forest streams is typically low, but may be sufficient to support populations of grazing (scraping) invertebrates (March and Pringle, 2003; Brito *et al.*, 2006).

Food web studies have now been conducted in aquatic habitats in many regions including streams in New Zealand (Townsend *et al.*, 1998, Hogsden & Harding, 2012), alpine lakes in North America (Weidman *et al.*, 2011), Brazilian reservoirs (Okun *et al.*, 2008) and streams in Japan (Kawaguchi and Nakano, 2001). However, the majority of these studies have been concentrated in temperate, European and North American streams and few have been undertaken in the tropics (Dudgeon, 2008). Thomson *et al.*, (2012) stated that if we are to make reliable generalizations about global drivers of change, we need to improve our understanding beyond the current reliance on data from species-poor temperate systems. Thus, while commonly used model food web systems have served us well in terms of forming new theory, more diverse and potentially more complex systems such as those in the tropics, might behave differently (Thompson *et al.*, 2012). However, studies of tropical aquatic food webs have so far demonstrated similarities in major environmental drivers to

temperate streams, despite differences in the taxonomic composition of the fauna (see for example Yule, 1996; Winemiller and Jepsen, 1998; Lau *et al*., 2009).

Typically food-web studies have been undertaken on small spatial scales, yet the importance of cross-ecosystem movements of materials that support local stream food-webs has been clearly demonstrated (Polis *et al.*, 1997). Numerous studies have confirmed the importance of detrital inputs in shaping forested stream food webs (Wallace *et al.*, 1997; Dudgeon and Wu, 1999). Food webs have also been shown to be dynamic, with taxa, links and aspects of structure changing over time and space, as demonstrated for freshwater systems by Warren (1989), Close and Lake (1994), Tavares-Cromar and Williams (1996), Thompson and Townsend (1999) and Woodward *et al.* (2005b).

In agricultural landscapes we might expect that in-stream primary production will provide the main support of the aquatic invertebrate community. For example, Bunn *et al.* (1997) studied in-stream ecosystem processes in a tropical lowland stream in far north Queensland by measuring community metabolism and analysing stable isotopes. The stream catchment had been extensively cleared for the cultivation of sugarcane, and in the absence of riparian shading, aquatic and semi-aquatic macrophytes choked the stream channel. They observed that stream metabolism switch between autotrophic and heterotrophic metabolism depending on cloud cover. On cloudy days dissolved oxygen become depleted especially at the stream bottom resulting in anoxia. Stable-isotope data indicated that little of the primary production from sugar cane or other C_4 plant was transferred into the aquatic food web. The only significant contribution of C_4 carbon was to the diets of some larger predatory fish, which must be directly dependent on terrestrial prey. In conclusion they stated that in the absence of significant riparian inputs of C_3 carbon, it appears that in-stream primary production supported the aquatic invertebrate community. In New Zealand Hicks (1997) conducted a study of stable isotope of carbon and nitrogen comparing forested and pasture stream communities in the Waikato region and showed that food webs in the shaded forest streams were based on allochthonous material (conditioned leaf litter and terrestrial invertebrates). In contrast autotrophs in the forested streams did not contribute significantly to the C source of the food web, instead, the C source of food webs in the unshaded pasture streams were a mixture of allochthonous and autochthonous material. Conditioned leaf litter appeared to have contributed to the pasture stream food webs, and the $\delta^{13}C$ and $\delta^{15}N$ of some samples of epilithic diatoms indicated their consumption by invertebrates in pasture streams. Subsequently, Thompson and Townsend (2004) compared forest and grassland streams in order to determine the food web structure in relation to energy availability, spatial

heterogeneity and ecosystem size with reference to riparian land use. They found that forested streams showed lower algal productivity and higher standing crops of organic matter than the grassland streams. Grassland sites showed a positive relationship between algal productivity and food chain length, whereas forest sites displayed a positive relationship between ecosystem size and food chain length. Therefore, algal production and organic matter standing crop were important determinants of invertebrate biomass and overall food-web structure. According to March *et al.* (2003) the dominant consumers in tropical island streams are often omnivorous freshwater shrimps that consume algae, leaf litter, insects, and other shrimps. Stable isotope analysis was used to investigate the relative importance of terrestrial and algal-based food resources to shrimps and other consumers and to determine, if the relative importance of these food resources changed along the stream continuum. They sampled $\delta^{15}N$ and $\delta^{13}C$ signatures of leaves, algae, macrophytes, biofilm, insects, snails, fishes, and shrimps at three sites along the Río Espíritu Santo, Puerto Rico. Their results indicated that signatures of basal resources were distinct at all sites, and two-source $\delta^{13}C$ mixing models suggested that shrimps relied more on algal-based carbon resources than terrestrially derived resources at all three of their sites. Their study supported the view that algal-based resources in tropical streams are very important to stream consumers, even in small forested headwater streams.

Gradient approaches have been used successfully in the study of food webs and take advantage of environmental shifts that occur along a gradient of natural systems. For example, a gradient approach was used effectively to understand the role of disturbance and resource supply in driving food-web structure in New Zealand streams (Townsend *et al.*, 1998). Other studies have used gradient approaches to assess how freshwater food webs change through time and space (Olesen *et al.*, 2010; Layer *et al.*, 2010b), and in response to resource availability (Rosi-Marshall and Wallace, 2002), climate (Layer *et al.*, 2010a; Layer *et al.*, 2010b; Layer *et al.*, 2011), disturbance (Parker and Huryn, 2006) and eutrophication (Rawcliffe *et al.*, 2010).

Gut content analyses have been included in numerous studies of stream food webs to categorize the nature of materials ingested by invertebrates and fish. However, although gut content analyses provides an immediate picture of food recently ingested, they do not indicate whether the ingested materials are digested or assimilated (Rounick *et al.*, 1982). In contrast stable isotope mixing models can sometimes be used to determine the contributions of food types (e.g., autochthonous and allochthonous organic matter) to an animal's diet (Phillips,

2001). Thus in the simplest mixing models two food sources can be partitioned using their stable carbon signatures (Phillips, 2001).

The aim of my study was to compare food web structure and properties in highland tropical streams flowing through catchments differing in land use. To do this I used a combination of stable isotope and gut analysis techniques. I expected that forested stream food webs would be dominated by allochthonous inputs such as coarse particulate organic matter (CPOM) and that maize streams would switch to autochthonous algae driven food webs. I also expected that maize stream food webs might be enriched with C^{13} due to maize being a C4 plant. The likely response of tea plantation streams is less obvious as leaching from tea plants may produce unusual effects on stream food webs.

Methods

Study sites

The study was carried out on the Mambilla Plateau, in the south east corner of Taraba State, Nigeria (11º - 6º E and 6º - 7º N). The Plateau has a tropical montane climate which is described briefly in chapter three of this thesis.

Sampling was undertaken between October 2011 and January 2012. Nine streams (second and third order) were sampled; three in forest, three in tea plantations and three in maize fields, respectively (Fig. 1). The forested sites were within mature submontane forest in the Ngel-Nyaki Forest Reserve. Maize and tea farming are common on the Mambilla Plateau, the tea plantations being well established crops. However, cultivation of maize in the study catchments started in 2008 and since then crop planting and livestock grazing have alternated on a yearly basis (i.e., shifting cultivation). The maize crop is rarely planted right up to the stream margins and grass or shrubs form riparian buffer zones up to approximately 50 m wide between the crops. Trees were native Afromontane species (*Deinbollia pinnata, Santiria trimera, Rafania* sp., *Croton macrostachyus, Anthonotha noldeae, Acacia senegalensis, Polyscius fulva, Syzygium guineense, Beeilschmedia* sp., *Pouteria altissima* and *Bridelia speciosa*).

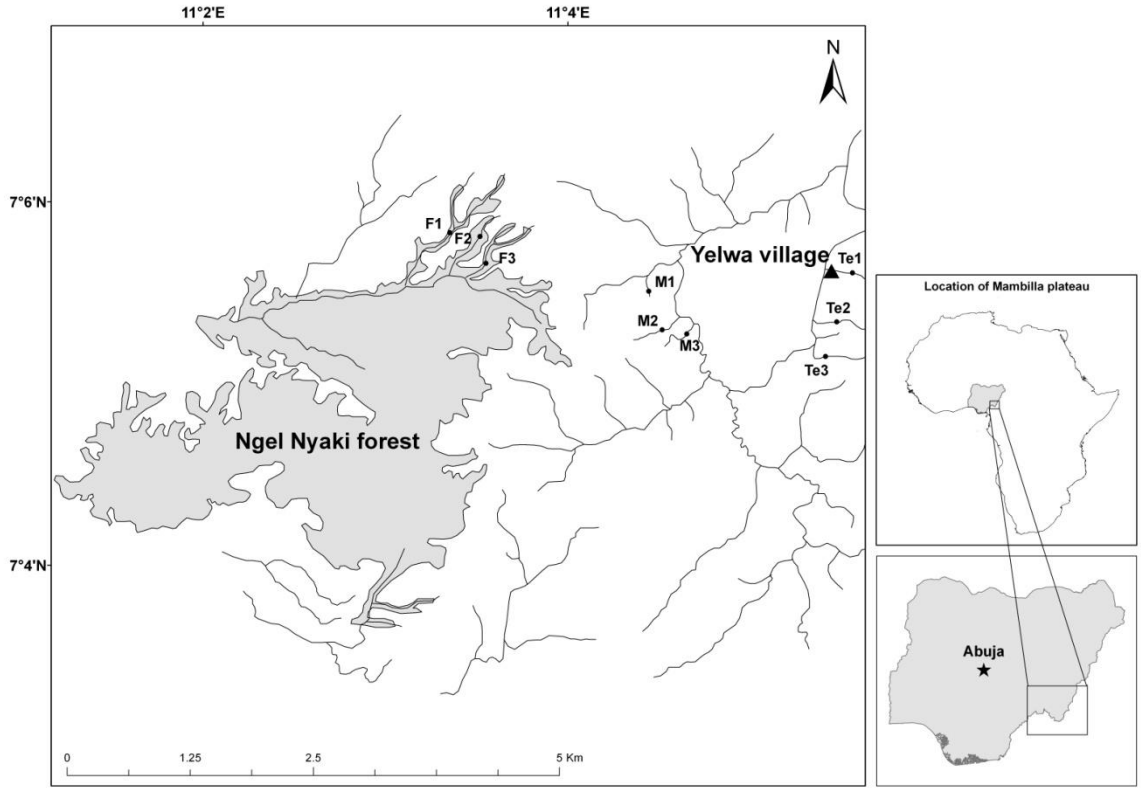

Figure 1: Location of sampling sites within the study area near Ngel-Nyaki Forest Reserve, Mambilla Plateau, Taraba State, Nigeria. Site abbreviation of streams flowing through: F = forest, Te = tea plantations, M = maize fields.

Bank-full stream width ranged from 4 to 12 m and substrate ranged from sand to large boulders. Basic water chemistry was similar in all nine streams; pH was 5.6–7.8, specific conductivity 30–110 µS 25 cm^{-1} and oxygen 56–80-% saturation. More detailed physico-chemical data for these nine streams are given in chapter four.

Basal food resources - algae & detritus

Basal food resources (source of carbon derived from terrestrial or in-stream producers) including fine particulate organic matter (FPOM) and algae were sampled for biomass and stable isotopes analyses. Dissolved organic matter (DOM) could not be measured due to logistical issues. A single FPOM sample was collected from the water column at each site using plankton net (60 µm mesh), which was deployed for approximately ten minutes to collect enough material for analysis (approx. 1-2 gm DW). The FPOM sample was filtered through Advance GC50 glass fibre filters (0.5 µm pores size), oven-dried at 60ºC for 48 h, and weighed. Filters were then ashed following Benfield (1996). Additional FPOM samples

were collected for stable isotope analysis following the same procedure. After filtration, the latter samples were oven-dried and ground with a pestle and mortar.

For each stream, biomass of CPOM was extracted from four benthic samples taken with a hand net (30 cm x 30 cm, 500 µm mesh size). Inorganic substrates were separated from CPOM by hand-picking. Dry mass (DM) and ash-free dry mass (AFDM) of each litter sample were determined following Benfield (1996), and a single ground sample from each stream was analysed for $\delta^{15}N$ and $\delta^{13}C$.

Benthic algal biomass was obtained by scraping five randomly selected stones (50 mm^2 each) from the stream bed using a wire brush and washing the composite slurry into pottles. These samples were later filtered using a syringe and filter paper (Whatman glass microfiber filters 0.75 µm pore size, 50 mm diameter disks) dried and weighed in the laboratory to (0.01 mg).

For stable isotope analysis sample of filamentous algae were collected by hand, and transported in water to the laboratory. After drying, each sample (57–256 mg DM) was ground with a pestle and mortar prior to analysis of stable isotope values.

Benthic invertebrates and fish

Fish and benthic invertebrates were collected from riffles during the dry seasons (October to March) of 2010 and 2011. Benthic invertebrates were collected from 15 cobbles and boulders in riffles in each stream (n = 45 cobbles and boulders/treatment; cobbles and boulders diameters 4–35 cm) with a triangular hand net (200–400 µm mesh) placed immediately downstream.

Invertebrates were placed in Eppendorf tubes, which were taken to the laboratory on ice containers. Two common species of fish, *Tilapia zilli* (Cichlidae) and *Clarias lazera* (Clariidae) were collected from pools with a hand net and used for gut content analysis and stable isotope determination. Samples collected for gut content analyses were frozen and preserved later in 70% ethanol.

In the laboratory most benthic invertebrates were identified to family level and some to subfamily or lower. Only the most numerous taxon in each family was used in analyses (Appendix 2). Between five to 20 individuals of common consumer taxa were gutted and examined for food contents. All predatory invertebrates and fish taxa collected were examined for gut contents, the numbers of individuals of each ranging from 10 to 15.

If large numbers of individuals of a particular taxon were available (e.g., the oligoneuriid mayfly *Elassoneuria*), three to five individuals of up to three size classes were

examined to assess variation in feeding with animal size. Guts of invertebrates were removed, mounted on slides in lactophenol-PVA stained with lignin pink, and examined under a Nikon SMZ 800 stereo dissecting microscope at up to 400 x magnification. Up to 10 fields were examined on each slide with a gridded graticule inserted in the eyepiece. At each grid crosshair, the four nearest food items were identified until 200 items had been identified on a slide. However, fewer than 100 items were identified on some slides from almost empty guts. Gut contents were categorised as filamentous algae, diatoms, fungi, CPOM ≥ 1 mm (usually leaf litter, wood, and gravel), FPOM < 1 mm (usually amorphous detritus) and animal parts. Most prey items were identified to family using slides and the drawings in Dudgeon (1999). The relative abundance of each category of prey type was calculated.

Stable isotope analyses

In the laboratory invertebrates were kept alive in bottles of water for ~ 15 hours to clear guts before freezing (Cummins, 1973; Parkyn *et al.*, 2001) and were later rinsed with distilled water to remove non-animal material (e.g., detritus). Digestive tracts of the crab (Brachyura; Potamonautidae) were removed to avoid contamination by non assimilated materials. Snails were decalcified with 1N HCL and rinsed in distilled water several times as in Mantel (2003). Samples of lateral muscle tissue ≥ 100 mg DM were taken from fishes, being careful to avoid bones and scales. Plant samples were rinsed and handpicked to remove biofilm, detritus and invertebrates.

All samples were oven dried at 60ºC for 48 h, ground to a fine powder with a mortar and pestle, weighed and stored in Eppendorf tubes. In order to avoid contamination all grinding equipment was cleaned using 100% ethanol and Kim wipes before the grinding of a new sample. Subsamples of all animal (c. 1mg ± 0.15 DW) and plant samples (algae, CPOM, moss) (c. 3mg DW) were used for analysis. Each individual sample was weighed to 0.1 mg. Each sample was transferred to an 8 mm x 5 mm tin capsule using a clean spatula.

Tin capsules were placed in a 96-well plastic culture tray, and sent to the stable isotope facility, University of California, Davis. Results (‰) are reported as $\delta^{13}C$ and $\delta^{15}N$, i.e., the difference between the sample and an international standard (air for N and Peedee Belemnite for C; Peterson and Fry 1987). Analytical precision was 0.3%.

Properties of food webs

A range of food web attributes were calculated using gut content data following methods in Mantel (2004): species richness (or web size, S); number of links (or number of "ones" in the

food web matrix, L); mean and maximum length of all food chains; fraction of basal species (species with no prey, i.e., basal food resources); fraction of intermediate species (species that have predators and prey); fraction of top predators not preyed upon; fraction of omnivores (animals feeding at >1 trophic level); predator-prey ratio (number of predators divided by number of prey); trophic connectance (C_T = L/S[S-1]; realised connectance (CR)

CR = L/{S^2 -[({pp + ba]S) + (S - {pp + ba]) + (pr{pp + ba]) (Jaarsma *et al.*, 1998). The terms used in CR are: pp- the number of primary producers (i.e., the numbers of diatoms, filamentous algae and unicellular algae) ba- the number of nonalgal basal elements; and pr- the number of predators (Jaarsma *et al.*, 1998). Thus, C_T is the number of links found in the web divided by the potential number of interspecific interactions, whereas CR is the number of links found in the web divided by the potential number of links in the web assuming all links were possible (i.e., S^2) minus the number of links to non feeding basal species and links from predatory species to basal food resources that might be incidental as in Mantel (2004). Other metrics calculated included; linkage complexity (product ba})]}; of species richness and realized connectance, or SCR, (Briand, 1985); and linkage density (total number of links in the web divided by the total number of species, L/S; Pimm *et al.*, 1991).

The predator-prey ratio was calculated following the definition of Jeffries and Lawton (1985) such that 'preys' are primary consumers and predators are 'any species that eat prey even if they are themselves are preyed upon'. The prey-predator ratio was also calculated by dividing the sum of the intermediate and basal species in the web by the sum of the top and intermediate species (Cohen, 1977).

Biplot of $\delta^{13}C$ and $\delta^{15}N$ values of FPOM/CPOM, algae, benthic invertebrates, and fish were used to compare patterns of isotopic variation within and between sites (forest, tea plantation and maize). Given that $\delta^{13}C$ values of dietary items are usually conserved within 1‰ in consumer tissues (McCutchan *et al.*, 2003), the relative importance of alternative source of organic carbon assimilated can be assessed by the relative position of the consumer and potential food sources on the x axis of the bi-plot.

In contrast to carbon isotopes, nitrogen isotope ratios of consumer tissues typically are 2.5–3.4‰ higher than tissues of their food items (McCutchan *et al.*, 2003; Vanderklift and Ponsard, 2003), enabling $\delta^{15}N$ to serve as a rough indicator of trophic position in addition to refining estimates of source contributions based on $\delta^{13}C$ values (Winemiller *et al.*, 2011).

Stable isotope mixing models can be used to determine the contributions of food sources to a mixture in an animal's diet (Phillips, 2001). Phillips found that two food sources can be partitioned using the isotopic ratio for a single element (e.g., $\delta^{13}C$). In such a mixing

model, the isotopic value of the consumer falls between the dietary end-members (sources) and is considered to be mixture of them.

I created a mixing model using (SIAR V4) in R, SIAR is a software package designed to solve mixing models for stable isotope data within a Bayesian framework (Parnell *et al.*, 2008). The model is used to help untangle the relative contributions of differing food resources to the food web. It incorporated two elements ($\delta^{13}C$ and $\delta^{15}N$) and two sources (algae and leaves). Stable isotope data for all sites were used to run the model. The input data file for each site was made up of the means and standard deviations of stable isotope $\delta^{13}C$ and $\delta^{15}N$ data for consumers (fish, dragonflies, tipulids, crabs, mayflies and snails), food sources (algae and leaves) and trophic enrichment factors (TEF).

Results

Basal food resources - algae and detritus

Significant differences in the biomass of CPOM and algae, but not FPOM were found among streams with differing land uses. CPOM was significantly higher in forest than tea plantation and maize fields' streams, whereas, forested streams had the lowest algal biomass and maize streams the highest (Table 1).

Table 1: Mean biomass (± SE, n = 3 streams per land use) of basal food resources in streams across three land uses. FPOM = fine particulate organic matter, CPOM = coarse particulate organic matter, * indicates significant difference $p < 0.05$ and ** $p < 0.01$.

Sites	Forest	Tea	Maize	F - stat	P - value
FPOM (g/L)	4.0 (1.3)	3.0 (0.2)	1.3 (0.1)	0.187	0.834
CPOM (g/m^2)	6.0 (1.0)	3.2 (0.3)	2.0 (0.2)	8.727	0.016*
Algae (DW g/m^2)	2.2 (0.3)	3.0 (1.0)	5.0 (0.4)	37.599	< 0.001**

Gut contents

Eight benthic invertebrate taxa and two fish species were used for gut analysis. They represented 75% of the total benthic invertebrates collected. Only two taxa that were found in high numbers in all three land uses; the snail *Melanoides tuberculatus* (Thiaridae) and gyrinid beetles (Table 2). The gut contents of the snail differed between forest, tea plantation and maize field streams. Individuals from the forest streams had guts filled with FPOM (65%) and diatoms (3%) and those from the tea plantation and maize sites had filamentous algae as the dominant food items (80%) with smaller amounts of diatoms (10%). The gyrinid beetles

had a smaller mixed diet in all three land uses dominated by FPOM, diatoms and animal parts, especially Chironominae.

The Oligoneuriid mayfly was very abundant in forested streams and also collected in tea plantation streams. Its diet was similar in both land uses and was dominated by FPOM, and diatoms, indicating it may be a filter-feeder (Table 2). Similarly the filter feeding hydropsychid caddisflies (of which there were at least two distinct species) were also common in forested streams. Again in both land uses they had a mixed diet of FPOM (45%) and diatoms (25%). In contrast, the gut contents of perlid stoneflies, which were found in the forested streams, were dominated by animal prey (50–90%, primarily hydropsychids) indicating they were predators. Chironominae and Baetidae made up most of the rest of the prey of the perlids. Potamonautid crabs were common in forested streams and less common in other streams. In both forest and maize streams they consumed a wide variety of food items. In forested streams their gut contents were dominated by FPOM (10%) and CPOM (80%) of which 10% was wood and 70% leaves. The predominance of CPOM in gut contents indicated it was primarily a detrital shredder. However, in maize field streams where CPOM was not abundant, filamentous algae and FPOM dominated crab gut contents and a few invertebrate prey items also occured indicating they are omnivorous.

The guts of the gomphid dragonflies were dominated by animal fragments (70%), most of which were well fragmented and difficult to identify, although Chironominae seemed an important prey (20%). Dragonfly guts also commonly contained FPOM (10%) and diatoms (10%), although these may have been accidentally ingested or in the invertebrate prey they consumed. The tipulid *Leptotarsus* (Tipulinae) ingested mainly CPOM (90%) 80% of which comprised leaf fragments and 10% wood in forested streams. FPOM and algae were common in maize streams. *Leptotarsus* seemed to be an important shredder.

The two fish species *Clarias lazera* and *Tilapia zilli* consumed mainly animals (40–80% relative abundance) but also some CPOM. This CPOM may have been accidentally ingested. Dissected fish contained an average of three prey items per gut, predominantly mayfly and stonefly larvae (55–60%).

Amorphous materials of unknown origin were also found in many guts and were ignored in determining proportion of gut contents. These may have included accidental or "by catch" food, as well as body organs from animals dissected. Overall, FPOM (30%), filamentous algae (25%), CPOM (20%), diatoms (15%) and fungi (10%) were the most frequently encountered basal food items in the animals examined (Table 2), while

Chironomidae (9%) and Hydropsychidae (8%) were the most frequently prey able to be adequately identified in gut contents (Table 2).

Table 2: Dominant food found in the guts of each taxon within land use (R = rare, < 5%; C = common, 5–20%; A = abundant, > 20%). – = absent. Prey – indicates invertebrate prey taxa able to be identified in guts.

Land use	Consumer	Dominant food resources					
		CPOM	FPOM	Fil. algae	Fungi	Diatoms	Prey
Forest	Gomphidae	–	R	–	R	C	Chironomidae
	Gyrinidae	–	C	R	–	R	Hydropsychidae
	Hydropsychidae	–	R	A	R	C	–
	Oligoneuriidae	–	A	R	R	C	–
	Perlidae	–	C	–	–	R	Chironominae
	Potamonautidae	C	C	–	R	R	–
	Tipulidae	A	R	–	R	C	–
	M. tuberculatus	A	A	R	C	C	–
	Tilapia zilli	–	C	–	–	R	Perlidae
	Clarias lazera		C	–	–	R	Perlidae
Tea	Gyrinidae	–	R	R	–	R	Chironominae
	Hydropsychidae	–	A	C	R	C	–
	Oligoneuriidae	–	C	R	R	C	–
	M. tuberculatus	R	C	A	A	C	–
	Tilapia zilli	–	B	C	C	R	Baetidae
	Clarias lazera	–	B	C	C	R	Perlidae
Maize	Gomphidae	–	R	C	–	R	Chironomidae
	Gyrinidae	–	C	C	–	R	–
	Potamonautidae	R	C	C	R	C	Hydropsychidae
	Tipulidae	–	C	C	R	C	–
	M. tuberculatus	–	C	A	A	C	–
	Tilapia zilli	–	C	A	C	A	Chironomidae
	Clarias lazera	–	C	B	B	A	Chironomidae

Stable isotope values of basal food resources- algae and detritus

Biplots of $\delta^{13}C$ and $\delta^{15}N$ for basal food resources collected from riffles in forest, tea plantation and maize streams showed that FPOM was depleted in $\delta^{13}C$ enriched in $\delta^{15}N$ in forested streams compared to tea and maize streams (Fig. 2). For CPOM mean $\delta^{13}C$ and $\delta^{15}N$ values were intermediate in maize and tea streams but less enriched in forested streams (Fig. 2). Algae showed no difference in $\delta^{15}N$ between land uses, however again forested streams were depleted in $\delta^{13}C$.

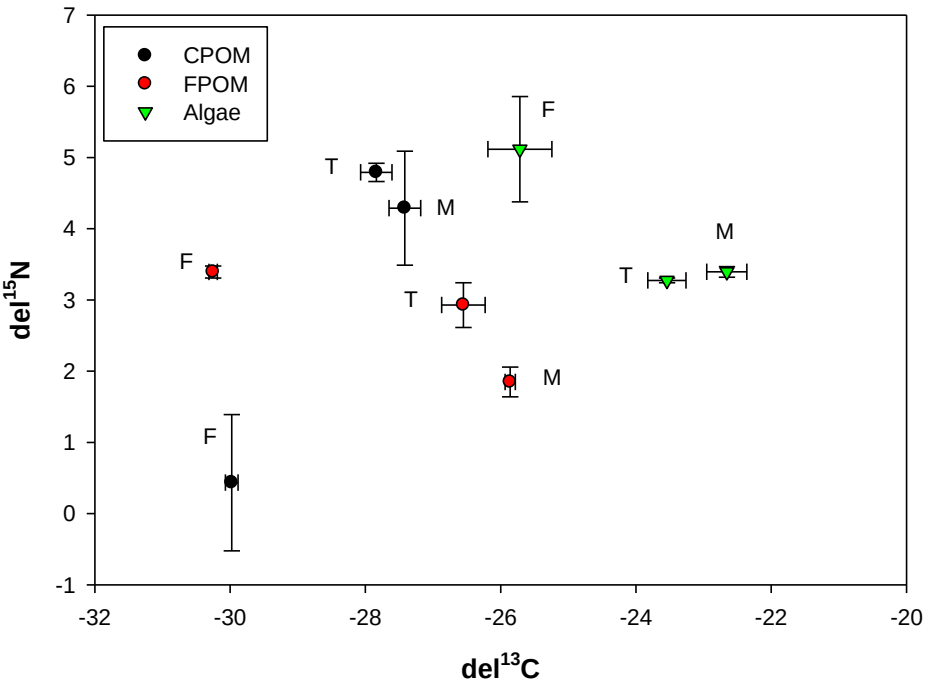

Figure 2: $\delta^{13}C$ and $\delta^{15}N$ biplots of algae, FPOM and CPOM collected from riffles in streams flowing through; F = continuous forest, T = tea plantation = and M = maize field on the Mambilla Plateau. Mean ± SE, n = 3.

Stable isotope signatures of primary and secondary consumers

For primary consumers (e.g., snails, mayflies and tipulids) $\delta^{13}C$ and $\delta^{15}N$ signatures were generally similar, with $\delta^{13}C$ values varying little between consumers in differing land uses (Fig. 3). One notable exception was the mayflies which were highly enriched in $\delta^{15}N$ in forested streams consistent with the high $\delta^{15}N$ signature of FPOM and algae in these systems and with filter feeding by the mayfly *Elassoneuria.* In contrast, the snails in maize streams had the lowest $\delta^{15}N$ (Fig. 3).

For the main predators and omnivores (dragonfly larvae, crabs and fish) considerable overlap occured between species across land uses (Fig. 4). Fish had strongly enriched $\delta^{15}N$ signatures (10–12‰), which overlapped among land use types. In contrast, $\delta^{13}C$ values were similar although forested stream fish were slightly depleted in $\delta^{13}C$ (Fig. 4). Of the other taxa, the crabs in tea plantations had markedly lower $\delta^{15}N$ signatures indicating greater consumption of algae and FPOM in these streams. The isotope signatures of the predators and omnivores integrate dietary pathways within food webs and the results indicate they fed

on a variety of prey consuming varying amount of allochthonous and autochthonous carbon. Biplots for all analysed taxa and food resources are brought together for comparison in Fig 5. The results of the stable carbon and nitrogen analyses showed clearly differences between food sources of similar animals in different land uses.

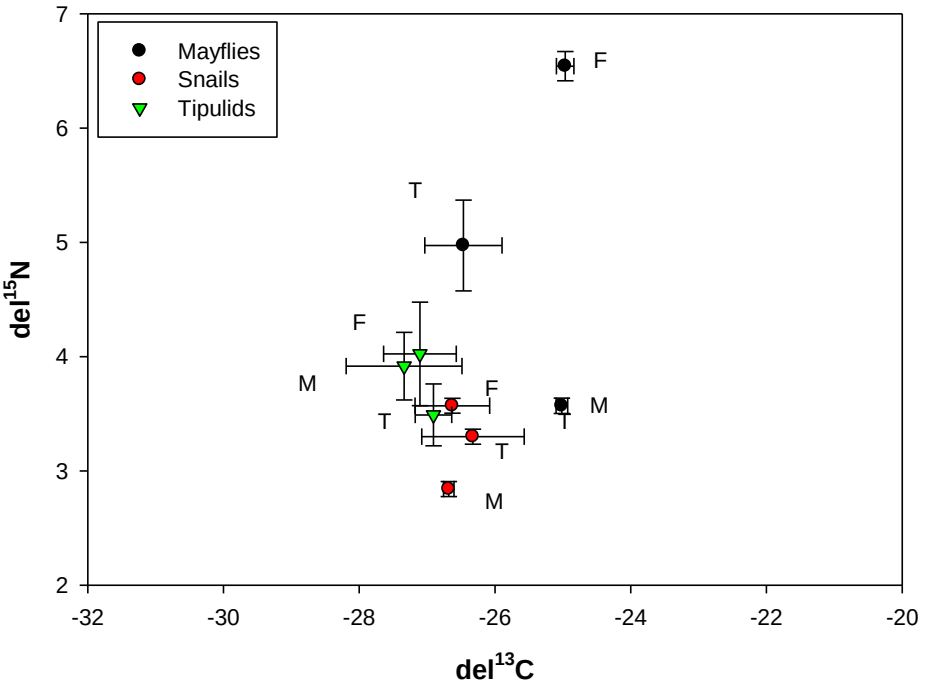

Figure 3: Stable isotope biplots of primary consumers collected from riffles in streams flowing through; forest = F, tea plantation = T and maize field = M. Values are mean ± SE, n = 3.

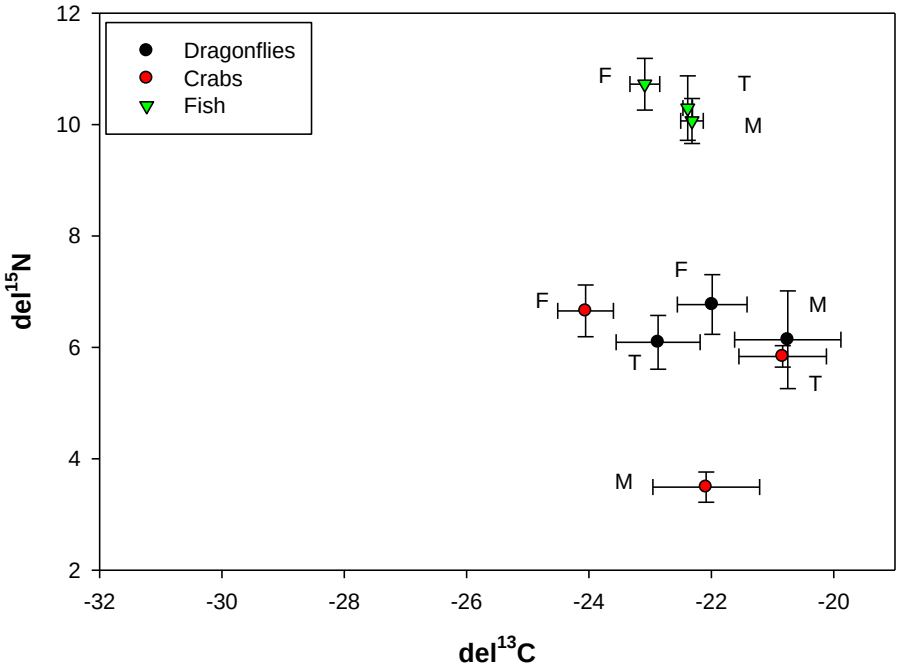

Figure 4: Stable isotope biplots of predators and omnivores (dragonflies [Gomphidae] and fish) and a macro-shredder (potamonautid crab) collected from riffles in streams flowing through; forest = F, tea plantations = T and maize fields = M. Values are mean ± SE, n = 3.

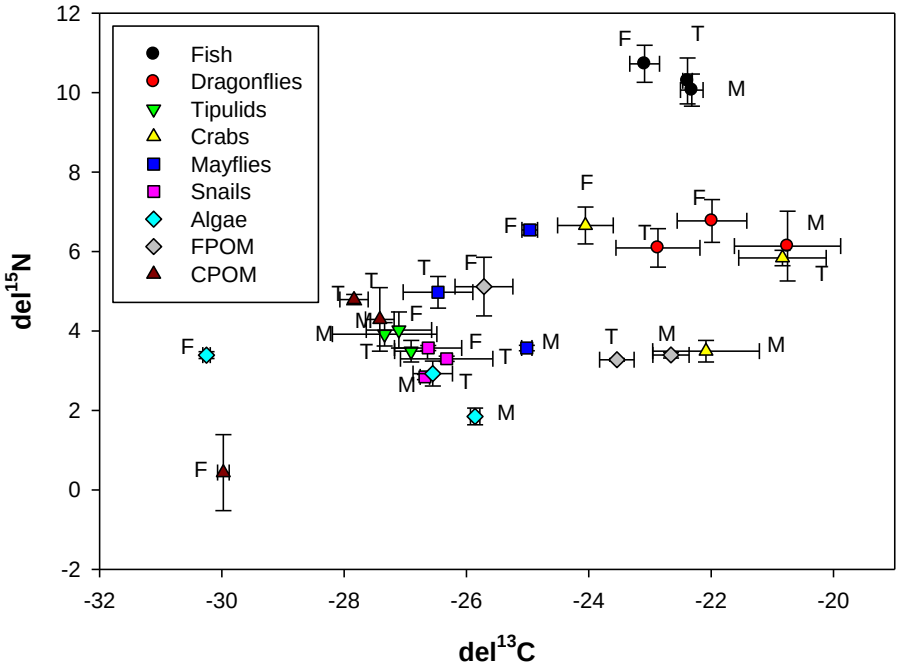

Figure 5: Stable isotope bi-plots for all primary and secondary consumers collected from riffles in streams flowing through forest, tea plantations and maize fields on Mambilla Plateau. Values are mean ± SE, n = 3.

Mixing model

A mixing model analysis for consumer taxa from each stream indicated forested stream consumers were tightly distributed but more variable in tea and maize plantation streams. Because the $\delta^{13}C$ signatures of algae and leaves overlapped strongly in the forested and tea plantation streams the mixing model was not able to determine the relative importance of the two food sources in the diets of consumers. However, because $\delta^{15}N$ signatures of consumers tended to be more aligned to those of leaves, this suggests a greater use of allochthonous food sources in all three stream types. The proportions of algae and leaves incorporated by consumers as estimated by the mixing models confirm that algae appear to be less important than leaves, although comparison of the credibility intervals (data not shown) indicated the evidence is not strong. Interestingly, the predatory taxa, dragonflies and fish, were supported more strongly by algal-based webs.

Web properties

Food web attributes differed significantly between land uses (Table 3). Forested streams had significantly larger food webs (a mean of 26 taxa) compared to tea and maize which had means of 17 and 16 taxa, respectively (Table 3).

Similarly the number of links (L) were also, highest in the forest (mean 183) followed by the tea plantation (mean of 114) whereas in maize fields it was lowest (mean 79). Maximum chain length (MCL) was similar for both forest and tea plantations (mean 3) but differed with maize field (mean 2). Predator: prey ratio was highest in maize field streams (mean 4) but little difference was observed between forested streams and tea plantation streams. Trophic connectance (CT), realized connectance (CR) and linkage density (L/S) did not differ between the three (forest, tea plantation and maize fields) stream types. However, linkage complexity (SCR) differed significantly in the three streams ($F_{2, 6} = 8.812$, $P = 0.016$, Table 3).

Table 3: Food web properties for each stream group on the Mambilla Plateau calculated from the gut content analyses and kick sample collected from nine streams. Values shown are group means (±SE) and ranges, n = 3 streams per type. *: Indicate significant difference ($P < 0.05$) ANOVA.

Stream type	**Forest**		**Tea**		**Maize**		**F-stat**	**P-value**
Food web attributes	**Mean ±SE**	**Range**	**Mean ±SE**	**Range**	**Mean ± SE**	**Range**		
Web size (S)	26 ± 2.02	23 - 28	17.0 ± 2.02	15-20	16.06 ± 1.20	15-20	15.509	0.004**
No. of linkages (L)	183.06 ± 28.01	140 - 234	114.06 ± 20.05	80-148	79.33 ± 13.09	60-104	6.347	0.033*
Max. food chain length (MCL)	3 ± 0.00	3.0 - 3.0	3 ± 0.0	3–3	2.66 ± 0.33	2–3	1	0.421
Fraction of basal species	0.17 ± 0.02	0.14 - 0.21	0.25 ±0.03	0.19-0.21	0.20 ± 0.01	0.18-0.22	2.776	0.14
Fraction of intermediate species	0.72 ± 0.03	0.65 - 0.78	0.68 ± 0.03	0.64-0.76	0.74 ± 0.03	0.68-0.78	0.646	0.556
Fraction of top predators	0.09 ± 0.02	0.04 - 0.13	0.05 ± 0.01	0.04-0.06	0.05 ± 0.03	0.05-0.11	0.888	0.459
Predator: prey ratio	1.36 ± 0.07	1.5 - 1.35	3.0 ± 0.2	2–3	4.05 ± 0.5	3.0 - 5	17.337	0.003**
Trophic connectance (CT)	0.27 ± 0.00	0.17 - 0.46	0.36 ± 0.0.03	0.31-0.41	0.25 ± 0.05	0.19-0.37	0.819	0.484
Realized connectance (CR)	0.04 ± 0.1.72	0.03 - 0.05	0.06 ± 0.01	0.04-0.07	0.05 ± 00	0.05-0.06	2.384	0.172
Linkage density (L/S)	6.72 ± 0.02	4.82 - 10.2	7.07 ± 0.44	6.61-7.91	4.8 ± 5.77	3.89-6.33	1.189	0.367
Linkage complexity (SCR)	3.07 ± 0.37	2.4 - 4	2.28 ± 0.03	1.11-2.31	1.29 ± 0.10	1 - 2.21	8.812	0.016*

Discussion

Streams in all three land uses included a range of basal food resources including FPOM, CPOM and algae and my gut analyses indicated that bacteria and fungi were also common. Not surprisingly, CPOM biomass was significantly higher in the forested streams than in the other land uses whereas algal biomass was significantly higher in the maize streams. The food webs of forested, tea plantation and maize field streams on the Mambilla Plateau also incorporated an assemblage of insect crustacean and molluscan primary consumers, predatory insects, carnivorous fish and omnivorous crustaceans. There were a number of limitations in my food web calculations. The values estimated for all three food webs will have been affected by limitations in the taxonomic resolution for different taxonomic groups. For example, I was not able to identify and count different diatoms, filamentous and other algal taxa within each food web. Furthermore, my benthic invertebrate identifications were limited by poor taxonomic knowledge. However, my results fall within the range reported by Mantel *et al.* (2004) and Dudgeon *et al.* (2010).

Regardless of these issues my data show that the forested streams had more complex food webs due to greater numbers of taxa at multiple trophic levels. Forested streams had longer food-chain lengths, higher fractions of top predators and predator-prey ratios than in tea plantation and maize field streams. Gut content analyses showed that FPOM, filamentous algae and diatoms were all significant basal food resources in the forest, tea plantation and maize streams, whereas CPOM was only important in forested streams. The high degree of autochthony observed in the non-forested streams is consistent with findings from a number of tropical streams elsewhere (Bunn *et al.*, 1999; March and Pringle, 2003; Douglas *et al.*, 2005; Brito *et al.*, 2006; Jacobsen *et al.*, 2008) and is also typical of larger temperate streams and other sites where canopy cover is reduced (Finlay, 2001; Finlay *et al.*, 2002).

The importance of CPOM in my forested streams is consistent with many other studies. Allochthonous material (CPOM and FPOM) was the primary basal food source in food webs of a forested head water stream on Bougainville Island, Papua New Guinea (Yule, 1996), in a third order grassland stream in New Zealand (Jaarsma *et al.*, 1998), and in forested streams in the Appalachians Mountains, USA (Hall *et al.*, 2000). FPOM, presumably of allochthonous origin, was the major dietary component of consumers in Broadstone stream, a second order stream in southern England (Lancaster and Robertson, 1995; Schmid-Araya *et al.*, 2002), and in a forested third order stream in Ontario Canada (Travares-Cromar and Williams, 1996). However, in a forested Sri Lankan stream Costa and Fernando (1967) found

that algae dominated the gut contents of benthic invertebrates, although some fish species and larvae of a psephenid beetle, *Eubrianax* sp., ingested leaf litter.

Studies of stable isotope signatures have shown the importance of autochthonous resources to Ephemeroptera in forested streams in Hong Kong (Salas and Dudgeon, 2001) and more generally to food webs in forested as well as open-canopied streams and rivers (Rosenfield and Roff, 1992; Benfield, 1996; March and Pringle, 2003). The selection of less abundant algal resources might be based on their higher food quality, in terms of energy and protein content (Bowen *et al.*, 1995; Friberg and Jacobsen, 1999), and the easier digestion of algae compared with most aquatic macrophytes and leaf litter (Wallace *et al.*, 1987; Whitledge and Rabeni, 1997; Rabeni *et al.*, 2002) The dominance of oligoneuriid mayfly (*Elassoneuria*) which is probably a filter-feeder in forested streams resulted in FPOM being an important resource.

Omnivory appeared to be uncommon in the food webs of the three types of streams in my study on the Mambilla Plateau. Crabs were collected in forested streams, and were probably omnivorous, my gut content data showed ingestion of CPOM, FPOM and algae and limited animal fragments. However, the isotope data indicated they were enriched in $\delta^{15}N$ so they may also feed on primary consumers. On the other hand low amounts of animal prey ingested by crabs may reflect a genuine difference in food web dynamics between small streams and larger lowland tropical rivers. For example omnivory is widespread among consumers in large rivers with seasonal flow in tropical Australia and the Neotropics where food webs are dominated by relatively few strong interactors and macro-consumers that control energy flows through animal communities (Winemiller, 1990; Jepsen and Winemiller, 2002; Douglas *et al.*, 2005; Coat *et al.*, 2009). Given the scarcity of data on tropical stream food webs, and the potential for differences in food web attributes and energy flow between different-sized streams, the need for investigations on tropical streams similar to those undertaken on their temperate counterparts is evident (Dudgeon *et al.*, 2010).

Comparisons of my forested, tea plantation and maize streams indicated that the stable carbon and nitrogen ratios of basal food resources (CPOM and algae) and major consumers (dragonflies, craneflies, crabs, mayflies, snails and two benthic fish species) differed little between tea plantation and maize field sites, but showed greater differences with forested streams.

Based on the gut content analyses, the relative contributions of dominant food sources in the three stream types (forest, tea plantation and maize) showed that CPOM and FPOM were dominant in forested streams, whereas in the tea plantation streams filamentous algae

and fungi dominated most consumers' guts. However, in maize field streams filamentous algae and fungi were more important as food sources for animals. The isotopic mixing models suggested greater use of allochthonous food, although the wide confidence interval apparent in the models makes it difficult to draw firm conclusions. Overall however, my result indicated that both allochthonous and autochthonous resources supported the aquatic invertebrate populations in all streams.

Overgrazing, wild fire, and bush clearing for farming have been major ecological problems on the Mambilla Plateau. Ultimately, we require a better understanding of how human disturbances such as habitat destruction affect reciprocal flows of invertebrates and other resource subsidies between linked stream and riparian habitats. Ecologists have long recognized that degradation of riparian habitat can alter flows of resources like leaves, wood, and dissolved organic carbon to stream ecosystems (e.g., Likens & Bormann, 1974), but the impact of a reduction in terrestrial invertebrate fluxes to streams has rarely been considered (Likens and Bormann, 1974). Converting riparian forest to grassland (Kawaguchi and Nakano, 2001), the grazing of riparian zones (Young and Huryn, 1996) and changing the species composition of riparian vegetation (Mason and McDonald, 2006), can alter terrestrial invertebrate inputs to streams, thereby restructuring stream food webs (Baxter *et al.*, 2004). However, riparian disturbance can also affect many other factors including light, temperature, and channel morphology, so research is needed to assess interactions between these and allochthonous inputs.

The present study was undertaken to determine whether a combination of stable isotope ratios and gut content analyses could provide measures of food web structure in tropical highland streams draining catchments in which land use differed. My results tend to support generalizations made for other tropical stream ecosystems. In that they were neither simple in trophic structure nor could they be characterised as having a limited array of feeding interactions. In contrast, feeding interactions in some tropical rivers are dominated by macro-consumers, and consequently have somewhat simplified feeding interactions (Dudgeon *et al.*, 2010). Although macro-consumers (crabs) could be common at my sites, insect larvae and snails were the predominant primary consumers. Additionally, my results, especially the gut analyses, suggested that autochthonous resources may have been of greater importance in supporting aquatic invertebrate populations in forested streams than appears to be the case in many small temperate-zone forest streams, which are strongly dependent on allochthonous inputs (McLachlan and Ladle, 2009). However, even though autochthonous resources may have been of great importance to invertebrate in the forested streams my result shows that

algal biomass is much lower in these streams. This might have been due to constant grazing and rapid turnover of algal biomass.

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Chapter six

General discussion and conclusions

Summary of findings

Introduction

The goal of my research was to determine the effects of land use on benthic stream communities in highland tropical streams in Nigeria. Initially I reviewed the literature on the benthic ecology of tropical streams, then conducted an extensive survey of streams in Nigeria followed by experiments to test whole stream processes in streams with differing land use.

My literature review confirmed that studies on the ecology of benthic stream invertebrates in Nigeria are relatively limited in number, and that there has been little work on the effects of agriculture on Nigerian benthic communities, especially in the north-eastern part of the country (Chapter 1). Despite an increasing number of studies on tropical streams, faunas are still relatively poorly known, and there are significant taxonomic impediments to species or genus level identifications in many countries (Dudgeon, 2008).

Given the barriers to freshwater ecological work in Nigeria particularly lack of field guide and taxonomic keys for the identification of freshwater macroinvertebrates for students and researchers, I felt that an important contribution would be to develop a key and photographic guide to freshwater macroinvertebrates in my study area. The guide is not an exhaustive taxonomic key, but is aimed to help researchers and students get started in the field. The invertebrates that live in our rivers, streams, lakes, ponds and wetlands are fascinating and important in the ecology of fresh waters. The guide provides an introduction to their diversity and the means to recognise the many different types, from flatworms to insects. Photos, along with brief notes on ecology and distribution, help visualise the more commonly encountered families of freshwater invertebrates occurring on the Mambilla Plateau. Identification is typically to family level, and more detailed guides will be required to pursue identification further. I hope this guide will also serve as a sound foundation for future ecological research in Nigeria, in the same way that the Winterbourn and Gregson invertebrate key has arguably formed a basis for the advancement of stream ecology in New Zealand.

Benthic fauna

As far as I am aware the benthic invertebrate fauna of streams on the Mambilla Plateau has not been studied prior to this research. Therefore, it was deemed important for me to invest considerable time in sampling and identification of the fauna. Invertebrate groups found include crustaceans, molluscs and insects in the orders Ephemeroptera (mayflies), Plecoptera

(stoneflies), Trichoptera (caddisflies), Odonata (dragonflies), Coleoptera (beetles), Hemiptera (bugs) and Diptera (true flies). I recorded a total of 76 taxa with the highest in continuous forest streams and the lowest in streams with intensive crops.

Effects of land use

Comparisons between my tropical streams in the forest and agricultural catchments have shown various differences in the physical and chemical characteristics and ecological properties of streams with temperate regions. Obtaining an understanding of how tropical ecosystems response to land use is a major priority for management and conservation (Boyero *et al.*, 2009). I investigated the response of benthic invertebrate communities to a "gradient" of land use encompassing forest, riparian valley bottom forest fragments, tree plantations, crops and pasture. I found variable differences in invertebrate diversity, community composition and density between the land uses. The greatest difference was found between continuous forest streams, where the highest species diversity was found and streams running through intensive crops such as maize and cabbage. This is almost certainly due to differences in greater canopy cover in the forest which provide shading, markedly lower temperatures in the forested streams, and differences in substrate and channel stability. In my highland streams a number of compounding activities occurred that were difficult for me to adequately measure and account for, however. For example, livestock could occur in all streams (even in continuous forest), while human use of streams for cleaning was also widespread.

Despite these factors a number of physical and chemical parameters were shown to differ between land uses. Streams with crops, such as maize and cabbage, were opened-canopied and had abundant decomposing crop matter on their beds, thereby probably decreasing dissolved oxygen concentration and increasing biochemical oxygen demand (although I lacked the ability to measure these factors in Nigeria).

Several pollution sensitive taxa (e.g., mayflies in the family Heptageniidae and Oligoneuriidae, and perlid stoneflies) occurred primarily in forested streams. Forested streams were also rich in a number of caddisfly families, in particular Hydropsychidae, Polycentropodidae, Glossosomatidae, Leptoceridae, Limnephilidae, Philopotamidae, Sericostomatidae and Psychomyiidae. In contrast, taxa that were tolerant of poorer water and habitat quality (e.g., the dipterans Chironomidae, Tipulidae and Syrphidae) occurred in tea plantation and maize field streams. Interestingly, one of two morphologically distinct species of hydropsychid caddisflies was mainly found in forested streams, whereas the other occured in plantation and maize field streams as well. The dragonfly families Aeshnidae and

Gomphidae were found mostly in the crop and pasture streams associated with macrophytes and were absent from forested streams, whereas coleopteran (beetles) and some hemipterans (true bugs) were found at both forested and agricultural sites.

Multivariate analysis generally separated continuous forested sites from plantation and forest fragment sites. However, crops and pasture communities were highly variable and in some cases were more similar to forest fragment streams and in other cases more similar to plantation streams. The separation of continuous forest from plantation and forest fragments was based primarily on the presence of Caenidae, Baetidae, Leptophlebiidae, Perlidae, Hydropsychidae, Lepidostomatidae and Tipulidae. The variability of communities in crop streams was probably due to high variability in farming intensity and buffer zone widths. Three other important taxa were Chironomini species A and the two gastropods, *Bulinus* and *Melanoides*. Chironomini made the greatest contribution to dissimilarity among all groups and were most abundant in continuous forest and crop streams. *Bulinus* and *Melanoides* were most abundant in crop and plantation streams and Ostracoda were abundant only in forest fragment streams.

Clearly farming (i.e., tea, maize, and cabbage) can have significant impacts on the benthic invertebrate assemblages of highland streams on the Mambilla Plateau, and my results highlight the importance of conservation and management of montane rainforest fragments in these regions to maintain high water and habitat quality of streams and diverse insect-dominated benthic faunas (Chapter 3).

What drives differences in communities with different land use?

In my survey I measured a number of physical and chemical parameters which might have brought about changes in benthic invertebrate communities including temperature, dissolved oxygen, pH, conductivity, substrate heterogeneity, sediment size, CPOM, algae, human and animal water usage (i.e., washing and drinking). A number of these factors were measured using field meters. However, because I could not accurately measure many other water parameters in Nigeria (e.g., turbidity, nitrate, phosphate) I do not have as robust a set of water chemistry results as I would have liked. Unfortunately, due to transportation and preservation issues nutrient analyses were not considered reliable and had to be excluded. Despite these limitations a physico-chemical pattern was observed across the four land uses (crops-pasture, plantations, forest fragment and continuous forest). Thus, high dissolved oxygen and low temperature were recorded in forest fragments and continuous forest, whereas, low dissolved oxygen (e.g., 40%) saturation and high temperature (e.g., 25 ^{o}C) were recorded in plantations

and crop/pasture (Fig. 1). These differences are liable to be important factors influencing stream communities and ecosystem processes on the Mambilla Plateau.

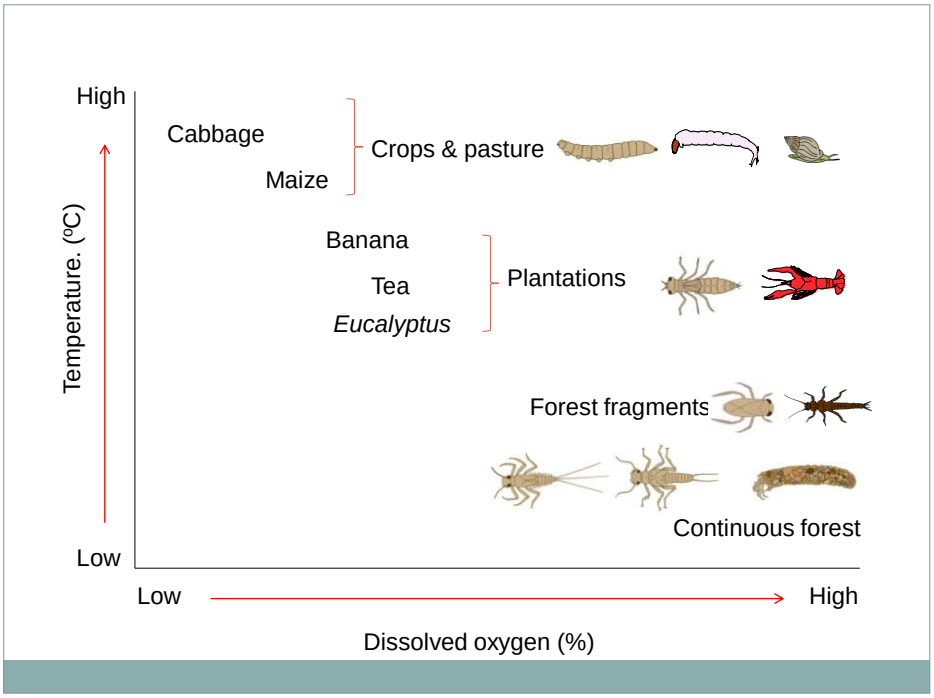

Figure 1: Simplified diagram showing the different land uses along a temperature-oxygen gradient.

In-stream processes

Litter decomposition is a key process linking nutrient cycling, energy transfer and trophic interactions in streams (Benfield *et al.*, 1977; Wallace *et al.*, 1997). Leaf-litter breakdown occurs through a combination of leaching of soluble compounds, microbial decomposition and conditioning physical abrasion and feeding by aquatic invertebrates (Goncalves *et al.*, 2006). I conducted a leaf litter decomposition experiment in nine small streams, three in continuous forest, three in tea plantation and three in maize fields to investigate the importance of land use and its effects on organic matter processing. Several tree species were in both forest and agricultural sites, but the most common in both was *Syzygium guineense* (Myrtaceae) and it was chosen for the litter breakdown experiment. My results indicated that leaf weight loss (when considered in relation to degree days) was faster in continuous forested streams than the other three land uses. Boulton *et al.* (2008) suggested that leaf breakdown in tropical streams might differ from temperate streams by relying more on microbial activity than shredding by invertebrates. My results indicate that in Nigerian forested streams where shredders occur they can play an important role in organic matter processing, just as in

temperate streams. Benthic invertebrate assemblages on the leaves differed between forest, tea plantation and maize field sites. Family richness was significantly higher in forest than in tea and maize. Invertebrate densities were higher in leaf packs from forested streams than tea plantation and maize streams, but variation among forested streams was also high. Shredders were collected in leaf packs from all the stream types, but few were found in the leaf packs from tea plantation and maize field streams and there were significantly more shredders taxa in forested streams than in the other land uses. Gut content and stable $\delta^{13}C$ and $\delta^{15}N$ analyses revealed that the crab (Potamonautidae) in forested streams fed primarily on leaves (CPOM), but also the larva of some families of insect shredders (probably Calamoceratidae and Leptoceridae) and Tipulidae played important roles in forest organic matter processing. This observation supports a widely held view that some tropical streams have abundant shredders including crabs (March *et al.*, 2001; Dobson, 2004; Dudgeon, 2008; Li and Dudgeon, 2008; Yule *et al.*, 2009).

The result of the leaf breakdown experiment suggests that land use in these tropical streams has a significant impact on organic matter processing but the mechanisms changed from microbial dominated leaf breakdown in the tea plantations and maize field streams, to shredder dominated breakdown in forested streams.

Food webs in highland tropical streams

Food webs can be particularly useful for helping us understand patterns of biodiversity and energy flow in ecosystems (Thompson *et al.*, 2012), but only brief consideration has been given to food webs and the trophic position in tropical streams (Dudgeon, 2008). Stream ecosystem functions such as nutrient cycling change with land use and can be expected to affect the nature of food chains and food webs and the strength of their internal links (Wallace *et al.*, 1997; Dudgeon, 2008).

I investigated the structure of stream food webs in the same nine streams used to investigate litter breakdown. I am not aware of any other food web studies in African tropical streams and therefore it is difficult to compare my results with other studies. Several tropical studies elsewhere have noted taxonomic "gaps", such as the loss of stoneflies in the tropics and suggested trophic replacement may occur in tropical streams. Trophic replacement has been suggested in Africa in the Baetidae which have been shown to have developed predatory, grazing and shredding genera (Boulton *et al.* 2008). Unfortunately my level of taxonomic resolution hindered any assessment of functional feeding differences in mayflies.

Not surprisingly my study showed that streams switch between allochthonous and autochthonous based systems depending on their catchment land use. Autochthonous foods have been shown to be the principal basis of consumer production in a tropical forest in Hong Kong despite the predominance of terrestrial detritus inputs (Lau *et al.*, 2009a). In the Nigerian forested streams this was not the case, and may have been due to the abundance of insect shredders which process allochthonous food resources.

A number of the consumers I found were omnivorous (e.g. crustaceans that fed on algae, leaf litter and insects). This is consistent with the recent suggestion by Thompson *et al.* (2012), that, omnivory can be an important process in many freshwater food webs. Some workers have suggested that warm water streams may have higher rates of omnivory than temperate streams (Lazzaro, 1997; Rawcliffe *et al.*, 2010; Thompson *et al.*, 2012). However, overall, omnivory seems to be less common in streams than lakes and also more common in marine and terrestrial systems than freshwater ones (Douglas *et al.*, 2005). The occurrence of omnivory in streams may reflect the predominance of short food chains in the lotic environment (Thompson *et al.*, 2007).

The food webs of the tea plantation streams were similar to those of maize field streams. That is, they were short and simple, with a maximum chain length of three and a mean of only 11 links (Fig. 2). However, the tea streams had considerably more invertebrate predators than the maize streams, and consequently maize streams may even have simpler food webs. In contrast, the forested stream food webs were more complex with more species, and although food chain length was short there were more links (Fig. 2). The complexity of forested food webs is consistent with other temperate stream food web studies, but is slightly surprising in the context of Mambilla Plateau streams. This is because continuous forest may not be the historic land use in this region. In fact the dominant historic land cover may have been more extensive grassland (Hazel Chapman pers. comm.). Thus, the high diversity and greater food web complexity in forested streams may be associated with greater habitat variability rather than historical evolutionary adaptation to forest. However, without more research this remains speculation.

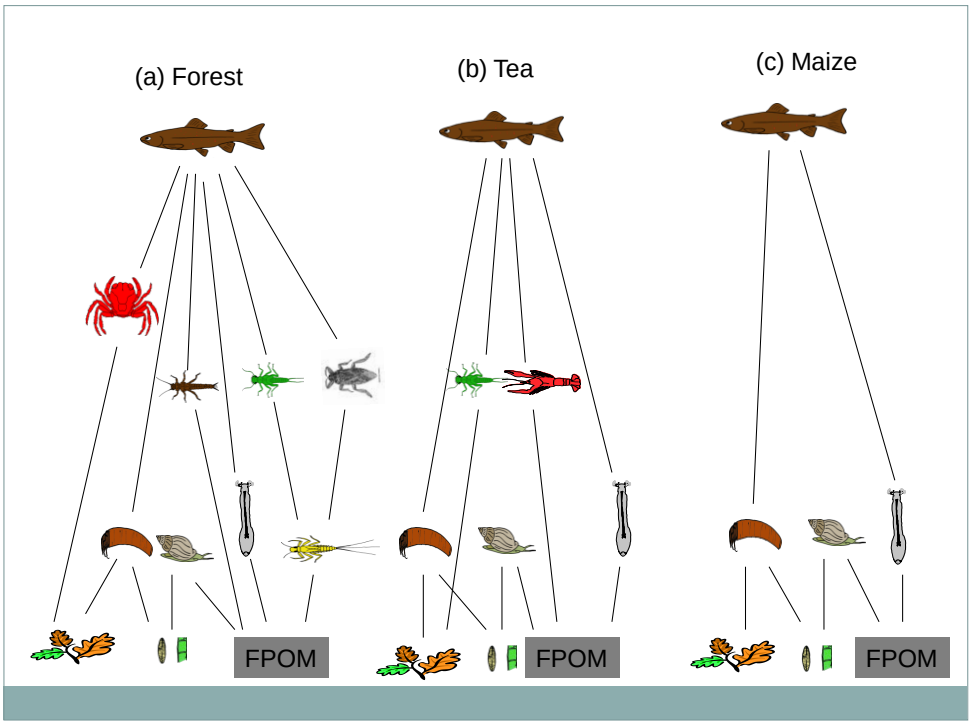

Figure 2: Simplified food web diagrams for streams in a) forest, b) tea plantations and c) maize fields. Links are based on gut content analyses. Each node represents a combination of several species (e.g., stonefly represents multiple predatory invertebrate species).

Why do we need to conserve freshwater biodiversity and invertebrate communities?

Invertebrates form a significant proportion of terrestrial and freshwater biodiversity (Mound & Gaston, 1993), they provide a number of critical ecosystem functions (Losey & Vaughn, 2006), and they serve as ecological link between terrestrial and aquatic ecosystems (Crown *et al*., 1995; Nakano and Muranaki, 2000; Baxter *et al*., 2005; Shawn and Michel, 2008). High biodiversity is often supported and probably enhanced by the exchange of resources between terrestrial and aquatic environments (Wallace *et al*., 1997), and invertebrates are considered in biomonitoring systems (Vane-Wright 1993; Woodroffe & Ginsberg 1998). The use of insects as bio-indicators for monitoring has developed substantially over the past few decades, and they are now widely used globally. Invertebrates are useful, often highly effective and informative indicators of other freshwater elements of biodiversity, ecosystem function and restoration, system health and associated threats, including invasive species (McGeoch, 2007). Although consideration of invertebrates has historically been neglected in conservation planning and management, substantial progress with surveys, systematics and bioindication means that it is now both feasible to incorporate them into conservation planning.

Are there threats to benthic communities on the Mambilla Plateau?

On the Mambilla Plateau, there are a number of land use issues posing threats to freshwater benthic communities. Examples include cattle entering into the forest for food and shelter, overgrazing of grassland by cattle, leading to increased erosion and run-off, annual burning, deforestation for timber and firewood, washing of harvested crops in streams and diversion of water channels for irrigation (Fig. 3). All of these activities occured in my streams and impacted on water quality which in turn affects stream communities. There is a need for better land management in order to conserve and protect these freshwater communities on the Mambilla Plateau. Future management could include the introduction of legislation to prohibit the indiscriminate discharge of agricultural chemicals (e.g., fertilizer and herbicides) and other waste materials directly into the aquatic systems.

Figure 3: A) bush fire deliberately burning grassland and forest, B) cattle in a forested stream, C) farmer washing maize in stream and D) stream channelized for irrigation.

Furthermore, there is a need for more effective protection of forest, both in terms of preventing cattle from entering the main forest and from using stream-side forest for watering and shelter. Constructing farm ponds to provide water for stock could reduce the need for

cattle to use forested streams, while allowing small patches of trees to grow for shelter. Similarly the provision of water reservoirs for washing harvested crops would help reduce crop contamination in streams. Furthermore, ensuring waste water drained into the ground and away from streams would help in reducing this type of pollution.

Finally, there is the need for more research by ecologists and scientists on the benthic ecology of the Mambilla Plateau. Government Agencies need to provide adequate support to researchers towards conservation and management of freshwater systems in Nigeria.

Additional studies in appendices

During the course of this research I conducted a number of additional studies on the ecology of highland tropical streams in Nigeria, which I have not included in the main text of the thesis. The first was a study on the effects of light traps on dragonflies on Mambilla Plateau (Appendix 5) and the second was an application of the maximum convex sum algorithm in determining environmental variables that affect Nigerian highland stream benthic communities (Appendix 6).

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Appendix 1: Summary of mean physico-chemical and taxa data of 55 streams surveyed in my study.

Site ID	Site name	Land-use	gps (E) start	gps (E) end	gps (N) start	gps (N) end	Livestock	Washing	Subst. Index
CF1	Augustine trans.	Forest	1103322	1103322	705243	705243	2	0	7.9
CF2	J.S.H 1	Forest	1103178	1103135	705014	705242	2	0	7.6
CF3	J.S.H 2	Forest	1103226	1103201	705117	705111	2	0	7.6
CF4	J.S.H 3	Forest	1103278	1103292	705124	705100	2	0	7.7
CF5	J.S.H 4	Forest	1103258	1103282	705102	705095	2	0	3.2
CF6	Luga Ginnaji 2	Forest	1103575	1103595	705753	705767	3	0	6.4
CF7	Luga ginnaji 3	Forest	1103511	1103523	705806	705815	2	0	7.8
CF8	Luga Ginnaji 1	Forest	1102968	1102978	706093	706099	3	0	7.8
CF9	Luga Ginnaji 8	Forest	1102942	1102953	706147	706107	1	0	7.7
CF10	Luga Ginnaji 9	Forest	1102943	1102937	706113	706136	0	0	7.8
CF11	Luga Ginnaji 10	Forest	1102864	1102859	706034	706051	0	0	7.6
CF12	Luga Ginnaji 6	Forest	1103084	1103098	706031	706041	2	0	6.7
CF13	Luga Ginnaji 7	Forest	1103092	1103091	706029	706026	2	0	7.9
CF14	Luga Ginnaji 5	Forest	1103316	1103325	705914	705913	2	0	7.5
CF15	Luga Ginnaji 4	Forest	1103424	1103431	705875	705877	2	0	7.7
GR16	Fragment B1	Grassland	1104195	1104193	704858	704857	0	0	5
GR17	Alh. Lawan	Grassland	1104898	1104906	706064	705905	3	0	3
GR18	Alh. Yusuf 3	Grassland	1104727	1104728	706170	706173	4	3	4.5
GR19	Alh. Bayero 1	Grassland	1104559	1104536	705633	705645	3	2	5
GR20	Alh. Bayero 2	Grassland	1104438	1104443	705535	705511	3	2	3

Site ID	Site name	Land-use	gps (E) start	gps (E) end	gps (N) start	gps (N) end	Livestock	Washing	Subst. Index
GZ21	Counsellor 3	Grazing	1104549	1104562	704774	704758	2	0	5.6
GZ22	Counsellor 4	Grazing	1104039	1104039	704559	704552	2	1	6
GZ23	Alh. Dambi 1	Grazing	1103707	1103721	704031	704036	0	1	3
GZ24	Fragment. C	Grazing	1103942	1103927	704731	704752	1	0	6.2
GZ25	Alh. Kato 2	Grazing	1104699	1104994	705022	705013	4	0	3.8
MA26	Fragment A	Maize	1104548	1104533	704871	704894	3	0	7
MA27	Alh. Yusuf 1	Maize	1104395	1104377	705894	705905	4	0	4
MA28	Misa 1	Maize	1104568	1104546	705272	705222	2	2	3.2
MA29	Misa 2	Maize	1104592	1104606	705260	705238	1	1	3.3
MA30	Misa 3	Maize	1104642	1104629	705269	705244	3	0	3
CB31	Jacob 1	Cabbage	1104782	1104800	705207	705201	3	3	3
CB32	Jacob 2	Cabbage	1104779	1104801	705203	705192	1	1	3
CB33	Ruqaya 1	Cabbage	1104907	1104928	705183	705171	3	1	3
CB34	Ruqaya 2	Cabbage	1104907	1104925	705183	705200	2	2	3
CB35	Habiba K	Cabbage	1105235	1105255	705105	705119	1	3	3.8
BA36	Fragment B2	Banana	1104208	1104193	705055	705015	3	0	5.5
BA37	Alh. Isa 1	Banana	1103901	1103871	704577	704569	3	0	4.5
BA38	Mal. Ali	Banana	1105559	1105571	705533	705522	3	3	7.3
BA39	Head Master	Banana	1105497	1105518	705338	705348	4	1	3.4
BA40	Yelwa	Banana	1105404	1105467	705253	705269	1	3	4.3

Site ID	Site name	Land-use	gps (E) start	gps (E) end	gps (N) start	gps (N) end	Livestock	Washing	Subst. Index
TE41	Bobbo 1	Tea	1104849	1104861	705601	705551	3	1	3.8
TE42	Bapa Saidu 1	Tea	1104988	1104988	705560	705548	4	3	3.8
TE43	Bapa Zubairu 1	Tea	1105120	1105127	705567	705556	0	2	7.9
TE44	Mohamadu 1	Tea	1105200	1105201	705897	705874	4	3	3
TE45	God free 1	Tea	1105324	1105329	705924	705897	0	1	3
EU46	Yusuf 2	*Eucalyptus*	1104699	1104677	704868	704861	3	0	5.8
EU47	Alh. Dambi 2	*Eucalyptus*	1103679	1103670	704046	704059	5	1	4
EU48	Fragment D	*Eucalyptus*	1103772	1103753	704952	704957	4	1	7.3
EU49	Alh. Isa 2	*Eucalyptus*	1103735	1103017	705055	705015	3	2	4.4
EU50	Alh. Yusuf 2	*Eucalyptus*	1104639	1104619	706055	706075	4	2	3
FR51	Mustapha 1	Fragment	1105402	1105421	704077	704072	2	0	5
FR52	Counsellor 1	Fragment	1105401	1105390	704056	704039	2	0	5
FR53	Mustapha 2	Fragment	1105451	1105468	704321	704324	2	0	5
FR54	Alh. Umaru	Fragment	1105338	1105358	704602	704596	3	0	5.6
FR55	Jauro Saidu	Fragment	1105350	1105367	704941	704953	2	0	5.8

Site ID	Site name	Land use	pH	cond. µs	% DO	DO (Mg/L)	turbidity(m)	velocity(m/s^2)	Nitrite-N(g/m^2)
CF1	Augustine trans.	Forest	7.6	191	56	5.36	0.5	0.2	0.0125
CF2	J.S.H 1	Forest	7.6	218	76.6	7.3	0.5	0.5	0.0045
CF3	J.S.H 2	Forest	7.3	216	70.9	6.66	0.7	0.18	0.0032
CF4	J.S.H 3	Forest	7.3	207	67.9	2.63	0.7	0.3	0.0038
CF5	J.S.H 4	Forest	7	275	58.7	5.62	0.7	0.3	0.0039
CF6	Luga Ginnaji 2	Forest	7.2	280	69.2	6.13	0.5	0.3	0.002
CF7	Luga ginnaji 3	Forest	7.5	164.5	73.7	6.66	0.3	0.3	0.0174
CF8	Luga Ginnaji 1	Forest	7.4	115	79	8.45	0.5	0.3	0.002
CF9	Luga Ginnaji 8	Forest	6.4	88.5	61.7	5.43	0.5	0.26	0.0051
CF10	Luga Ginnaji 9	Forest	7.2	50.8	60.4	5.26	0.5	0.3	0.0043
CF11	Luga Ginnaji 10	Forest	6.4	30.6	61.7	4.27	0.2	0.2	0.002
CF12	Luga Ginnaji 6	Forest	7.3	130	70.1	6.4	0.5	0.25	0.0041
CF13	Luga Ginnaji 7	Forest	7.4	148	73.5	6.58	0.1	0.25	0.0031
CF14	Luga Ginnaji 5	Forest	7.1	124	50.6	4.56	0.5	0.16	0.002
CF15	Luga Ginnaji 4	Forest	7	151	67.6	6.2	0.5	0.16	0.002
GR16	Fragment B1	Grassland	5.9	60.1	40.5	3.66	0.5	0.2	0.002
GR17	Alh. Lawan	Grassland	6	126.4	64.9	6.41	0.3	0.26	0.002
GR 18	Alh. Yusuf 3	Grassland	7.2	36.2	41.1	3.4	1	0.3	0.0057
GR19	Alh. Bayero 1	Grassland	6.7	131.8	74.5	7.7	0.2	0.13	0.002
GR20	Alh. Bayero 2	Grassland	6.7	129.3	66.4	6.2	0.5	0.2	0.0023

Site ID	Site name	Land use	pH	cond. µs	% DO	DO (Mg/L)	turbidity(m)	velocity(m/s^2)	Nitrite-N(g/m^2)
GZ21	Counsellor 3	Grazing	6	115.6	54.4	4.83	0.5	0.2	0.0073
GZ22	Counsellor 4	Grazing	6.1	80	68.7	6.42	0.15	0.16	0.0038
GZ23	Alh. Dambi 1	Grazing	6.8	58.2	31.4	3.6	0.5	0.15	0.0036
GZ24	Fragment. C	Grazing	8.1	56.8	58.1	5.51	0.5	0.5	0.0048
GZ25	Alh. Kato 2	Grazing	7.1	290	57.8	6.9	0.5	0.15	0.002
MA26	Fragment A	Maize	6.3	283	77.1	7.19	0.5	0.3	0.0021
MA27	Alh. Yusuf 1	Maize	6	206	71	6.82	0.5	0.14	0.002
MA28	Misa 1	Maize	6	119.3	47.8	4.5	0.5	0.18	0.0024
MA29	Misa 2	Maize	6	115	69.9	7.16	0.2	0.16	0.0076
MA30	Misa 3	Maize	5.6	276	54.6	5.1	0.2	0.12	0.002
CB31	Jacob 1	Cabbage	6.8	138	50	5	0.2	0.1	0.0043
CB32	Jacob 2	Cabbage	7	258	54.4	4.66	0.5	0.2	0.002
CB33	Ruqaya 1	Cabbage	7	203	68.2	6.4	0.5	0.5	0.002
CB34	Ruqaya 2	Cabbage	5.7	197	61.3	4.95	0.3	0.16	0.002
CB35	Habiba K	Cabbage	6.1	136	39.3	3.32	0.2	0.5	0.002
BA36	Fragment B2	Banana	5.7	178	35.4	3.9	0.5	0.16	0.002
BA37	Alh. Isa 1	Banana	8.2	257	55.7	5.27	0.2	0.16	0.002
BA38	Mal. Ali	Banana	5.7	195	31.7	3.1	0.5	0.3	0.0022
BA39	Head Master	Banana	6.8	377	29.5	2.9	0.5	0.12	0.002
BA40	Yelwa	Banana	5.2	131	38.8	3.23	0.5	0.2	0.002

Site ID	Site name	Land use	pH	cond. µs	% DO	DO (Mg/L)	turbidity(m)	velocity(m/s^2)	Nitrite-N(g/m^2)
TE41	Bobbo 1	Tea	7.5	230	74.2	7.03	0.3	0.2	0.0063
TE42	Bappa Saidu 1	Tea	5.7	536	30.9	2.77	0.2	0.3	0.002
TE43	Bappa Zubairu 1	Tea	6.4	220	61.8	5.65	0.2	0.16	0.0022
TE44	Mohamadu 1	Tea	7.5	457	63.3	5.53	0.3	0.16	0.0092
TE45	God free 1	Tea	6.6	195	70.6	6.16	0.7	0.1	0.002
EU46	Yusuf 2	*Eucalyptus*	6.3	269	61.8	5.8	0.5	0.12	0.002
EU47	Alh. Dambi 2	*Eucalyptus*	6.8	434	40.7	4.17	0.2	0.16	0.0032
EU48	Fragment D	*Eucalyptus*	6.2	141	15.1	1.2	0.2	0.2	0.0023
EU49	Alh. Isa 2	*Eucalyptus*	8.4	117	55.5	6.27	0.5	0.15	0.0026
EU50	Alh. Yusuf 2	*Eucalyptus*	6.1	247	26.1	2.3	0.5	0.1	0.0047
FR51	Mustapha 1	Fragment	6.9	141	70.1	7.8	0.5	0.16	0.002
FR52	Counsellor 1	Fragment	6.9	132	73.4	7.51	0.5	0.2	0.002
FR53	Mustapha 2	Fragment	6.8	147	66.3	5.6	0.5	0.25	0.002
FR54	Alh. Umaru	Fragment	6.9	211	75.6	7.12	0.2	0.2	0.0023
FR55	Jauro Saidu	Fragment	7.4	164.6	57.6	5.1	0.5	0.2	0.0032

Site ID	Site name	Land use	DRPhos(g/m^2)	Phosphate(g/m^2)	MOSS(gm^2)	Algae (gm^2)	FPOM (g/L)	CPOM.1	CPOM.2(g)
CF1	Augustine trans.	Forest	0.0047	0.02	0.0211	0.0241	0.019	3.3454	2.0023
CF2	J.S.H 1	Forest	0.004	0.02	0.0313	0.0041	0.0034	0.3278	1.3122
CF3	J.S.H 2	Forest	0.004	0.02	0.015	0.0091	0.0037	1.4462	2.3885
CF4	J.S.H 3	Forest	0.004	0.02	0.0101	0.0066	0.0463	0.3934	0.2571
CF5	J.S.H 4	Forest	0.0079	0.024	0.0311	0.0878	0.0231	2.9296	2.0461
CF6	Luga Ginnaji 2	Forest	0.004	0.02	0.0152	0.552	0.0279	1.7474	3.7406
CF7	Luga ginnaji 3	Forest	0.004	0.02	0.0222	0.0302	0.0086	0.9706	0.7331
CF8	Luga Ginnaji 1	Forest	0.004	0.02	0.014	0.0331	0.0701	4.762	2.1708
CF9	Luga Ginnaji 8	Forest	0.004	0.02	0.0233	0.323	0.0114	2.7418	5.2084
CF10	Luga Ginnaji 9	Forest	0.004	0.02	0.0213	0.0311	0.0123	4915	0.9882
CF11	Luga Ginnaji 10	Forest	0.004	0.02	0.0332	0.0053	0.0053	3.6422	2.8701
CF12	Luga Ginnaji 6	Forest	0.004	0.02	0.0221	0.0175	0.0381	0.8046	1.8099
CF13	Luga Ginnaji 7	Forest	0.004	0.02	0.0112	0.0175	0.0058	0.563	0.3993
CF14	Luga Ginnaji 5	Forest	0.004	0.02	0.0101	0.013	0.0111	0.5914	1.4384
CF15	Luga Ginnaji 4	Forest	0.004	0.02	0.02	0.0247	0.0225	0.436	2.8859
GR16	Fragment B1	Grassland	0.004	0.02	0.0141	0.0331	0.0887	15.4897	10.0821
GR17	Alh. Lawan	Grassland	0.004	0.02	0.0547	0.073	0.208	2.0359	1.5736
GR18	Alh. Yusuf 3	Grassland	0.004	0.02	0.4668	0.0121	0.0133	11.4408	3.9222
GR19	Alh. Bayero 1	Grassland	0.0056	0.02	0.0131	0.0165	0.0308	1.5589	0.299
GR20	Alh. Bayero 2	Grassland	0.004	0.02	0.0111	0.018	0.0723	1.1345	0.5802

Site ID	Site name	Land use	DRPhos(g/m^2)	Phosphate(g/m^2)	MOSS (gm^2)	Algae (gm^2)	FPOM (g/L)	CPOM.1	CPOM.2 (g)
GZ21	Counsellor 3	Grazing	0.004	0.02	0.42	0.0958	0.2297	2.6703	2.4197
GZ22	Counsellor 4	Grazing	0.004	0.02	0.0326	0.09	0.138	6.2551	1.1165
GZ23	Alh. Dambi 1	Grazing	0.004	0.02	0.221	0.07	0.0277	0.9988	0.8268
GZ24	Fragment. C	Grazing	0.004	0.02	0.0197	0.0193	0.472	3.1356	4.9575
GZ25	Alh. Kato 2	Grazing	0.004	0.02	0.021	0.0075	0.0269	5.4664	3.2866
MA26	Fragment A	Maize	0.004	0.02	0.0681	0.023	0.102	3.9186	2.7997
MA27	Alh. Yusuf 1	Maize	0.004	0.02	0.0265	0.066	0.0396	1.4944	0.6712
MA28	Misa 1	Maize	0.004	0.02	0.1501	0.0162	0.039	4.6604	2.9297
MA29	Misa 2	Maize	0.004	0.02	0.0211	0.0325	0.009	0.8591	1.6266
MA30	Misa 3	Maize	0.004	0.02	0.0112	0.068	0.008	0.8748	3.2548
CB31	Jacob 1	Cabbage	0.004	0.02	0.0451	0.0441	0.0523	0.1603	0.2824
CB32	Jacob 2	Cabbage	0.004	0.02	0.0421	0.0541	0.0459	1.1908	2.2196
CB33	Ruqaya 1	Cabbage	0.004	0.02	0.0094	0.0292	0.0216	2.6322	0.7904
CB34	Ruqaya 2	Cabbage	0.004	0.02	0.0681	0.0982	0.0123	1.9253	1.8336
CB35	Habiba K	Cabbage	0.004	0.02	0.0201	0.0668	0.0271	5.836	3.4824
BA36	Fragment B2	Banana	0.004	0.02	601	0.005	0.168	1.9613	1.6402
BA37	Alh. Isa 1	Banana	0.0041	0.02	0.0062	0.085	0.0051	2.1069	1.3785
BA38	Mal. Ali	Banana	0.004	0.02	0.0395	0.0045	0.1308	2.497	6.013
BA39	Head Master	Banana	0.004	0.02	0.1035	0.005	0.0399	0.5007	0.2324
BA40	Yelwa	Banana	0.004	0.02	0.1001	0.0099	0.0294	0.4529	1.3685

Site ID	Site name	Land use	DRPhos(g/m^2)	Phosphate(g/m^2)	MOSS (gm^2)	Algae (gm^2)	FPOM (g/L)	CPOM.1	CPOM.2 (g)
TE41	Bobbo 1	Tea	0.0044	0.02	0.0321	0.0195	0.0216	2.0173	1.1548
TE42	Bappa Saidu 1	Tea	0.004	0.02	0.332	0.015	0.1559	3.3498	1.961
TE43	Bapa Zubairu 1	Tea	0.004	0.02	0.0744	0.0394	0.0074	0.239	3.7863
TE44	Mohamadu 1	Tea	0.004	0.02	0.0662	0.0402	0.0203	0.4896	0.8096
TE45	God free 1	Tea	0.004	0.02	0.0321	0.0391	0.0313	4.3016	2.8837
EU46	Yusuf 2	*Eucalyptus*	0.004	0.02	0.005	0.0901	0.2397	5.459	2.0484
EU47	Alh. Dambi 2	*Eucalyptus*	0.004	0.02	0.251	0.075	0.0041	1.892	1.1721
EU48	Fragment D	*Eucalyptus*	0.004	0.02	0.0035	0.0221	0.037	1.645	5.2275
EU49	Alh. Isa 2	*Eucalyptus*	0.0073	0.02	0.0153	0.0351	0.0175	0.7009	1.4111
EU50	Alh. Yusuf 2	*Eucalyptus*	0.004	0.02	0.2188	0.0169	0.0255	1.686	3.9856
FR51	Mustapha 1	Fragment	0.004	0.02	0.012	0.073	0.0684	2.0532	1.8609
FR52	Counsellor 1	Fragment	0.004	0.02	0.0113	0.0758	0.0311	2.6396	1.4841
FR53	Mustapha 2	Fragment	0.004	0.02	0.0234	0.012	0.0233	9.6566	3.3944
FR54	Alh. Umaru	Fragment	0.004	0.02	0.0351	0.0293	0.0057	4.4136	3.5654
FR55	Jauro Saidu	Fragment	0.004	0.02	0.035	0.032	0.0042	6.6643	5.3519

Site ID	Site name	Land use	CPOM.5 (g)	CPOM (gm²)	Ash 1 (g)	Ash 2 (g)	Ash 3 (g)	Ash 4 (g)	Ash 5 (g)
CF1	Augustine trans.	Forest	0.9782	1.82038	0.492	0.4035	0.1457	0.1009	0.1138
CF2	J.S.H 1	Forest	0.863	0.82034	0.0341	0.1154	0.4603	0.2018	0.3359
CF3	J.S.H 2	Forest	2.9009	1.93596	1.4297	0.1296	0.0939	0.6067	0.6172
CF4	J.S.H 3	Forest	1.8174	0.82108	0.1644	0.071	0.1696	0.0344	0.4532
CF5	J.S.H 4	Forest	1.8787	2.70868	0.5247	0.5075	0.2564	1.1802	0.3306
CF6	Luga Ginnaji 2	Forest	4.0961	3.8731	0.3245	1.2451	0.8875	0.8134	1.5068
CF7	Luga ginnaji 3	Forest	0.5294	1.01354	0.1286	0.0911	0.1822	0.3294	0.2884
CF8	Luga Ginnaji 1	Forest	1.3328	2.9278	0.3285	1.6558	1.4571	0.7747	0.8517
CF9	Luga Ginnaji 8	Forest	1.0975	2.96394	0.5603	1.2995	0.2723	0.2415	0.2128
CF10	Luga Ginnaji 9	Forest	0.7115	2.91845	0.0565	0.1337	0.0966	0.1025	0.1528
CF11	Luga Ginnaji 10	Forest	1.6832	2.60612	0.5303	0.7259	0.5347	0.311	0.238
CF12	Luga Ginnaji 6	Forest	1.3931	1.47956	0.1532	0.7065	0.0623	1.1327	0.3019
CF13	Luga Ginnaji 7	Forest	1.7168	0.89992	0.0544	0..0613	0.6898	0.1518	0.5151
CF14	Luga Ginnaji 5	Forest	1.4559	1.02658	0.2441	0.8244	0.3405	0.3318	0.5855
CF15	Luga Ginnaji 4	Forest	2.2011	1.88568	0.0628	0.1582	0.1154	0.0526	0.5439
GR16	Fragment B1	Grassland	12.0932	14.00194	4.0476	5.5288	3.5276	9.6146	4.3009
GR17	Alh. Lawan	Grassland	1.4574	1.96328	0.0961	0.2825	0.203	0.0861	0.179
GR18	Alh. Yusuf 3	Grassland	4.4195	6.11544	2.853	0.9773	0.9455	0.3644	0.4006
GR19	Alh. Bayero 1	Grassland	0.1956	3.55382	0.3523	0.1024	0.0709	0.2712	0.0203
GR20	Alh. Bayero 2	Grassland	3.9183	1.24698	0.3163	0.0705	0.3495	0.0808	0.5518

Site ID	Site name	Land use	CPOM.5 (g)	CPOM (gm²)	Ash1 (g)	Ash 2 (g)	Ash 3 (g)	Ash 4 (g)	Ash 5 (g)	Mean Ash	Elevation (m)
GZ21	Counsellor 3	Grazing	3.2626	2.9371	0.2629	0.6185	0.9184	0.2378	0.8303	0.57358	1595
GZ22	Counsellor 4	Grazing	1.5939	2.42294	0.2957	1.7159	0.1197	0.2136	0.2089	0.51076	1631
GZ23	Alh. Dambi 1	Grazing	0.248	0.6645	0.4425	0.357	6.3104	0.1919	0.1117	1.4827	1613
GZ24	Fragment. C	Grazing	1.5786	2.73426	1.6475	2.1399	0.3779	1.6211	0.8948	1.33624	1647
GZ25	Alh. Kato 2	Grazing	1.6039	2.90182	2.2464	1.5603	1.2191	0.1828	0.5351	1.14874	1598
MA26	Fragment A	Maize	1.8898	2.5575	1.2069	0.5426	0.3534	0.435	0.3669	0.58096	1607
MA27	Alh. Yusuf 1	Maize	4.9718	2.57222	0.4091	0.2191	0.327	1.4796	1.7846	0.84388	1587
MA28	Misa 1	Maize	3.6379	3.05492	1.5044	0.5857	0.6474	0.3996	0.8345	0.79432	1588
MA29	Misa 2	Maize	1.1978	1.27248	2.0793	4.6414	1.0075	0.8478	1.2758	1.97036	1596
MA30	Misa 3	Maize	1.0822	1.77054	0.4537	0.4393	1.4162	0.1756	0.2143	0.53982	1585
CB31	Jacob 1	Cabbage	2.529	0.83282	0.9149	0.3856	0.6304	0.2985	0.2293	0.49174	1596
CB32	Jacob 2	Cabbage	4.4633	2.02906	0.5409	1.0041	0.6998	0.2613	2.6489	1.031	1595
CB33	Ruqaya 1	Cabbage	3.1422	2.4109	1.0782	0.299	0.9827	1.0537	1.296	0.94192	1597
CB34	Ruqaya 2	Cabbage	1.7225	1.69182	0.9245	0.9229	0.1603	1.0569	0.3584	0.6846	1604
CB35	Habiba K	Cabbage	1.2379	4.82858	2.3678	1.3961	2.7571	2.8308	0.3697	1.9443	1619
BA36	Fragment B2	Banana	2.6353	1.92388	0.7998	0.5625	0.4406	0.9295	1.0497	0.75642	1600
BA37	Alh. Isa 1	Banana	0.9838	1.30062	0.2865	0.2382	0.2128	0.6173	0.4415	0.35926	2382
BA38	Mal. Ali	Banana	3.5966	2.56228	0.226	0.7809	0.0992	0.2037	0.3365	0.32926	1624
BA39	Head Master	Banana	1.3361	0.63152	1.552	3.5724	0.0788	0.1676	1.3709	1.34834	1636
BA40	Yelwa	Banana	1.2296	0.80224	0.142	0.4657	0.188	0.1326	0.3953	0.26472	1643

Site ID	Site name	Land use	CPOM.5 (g)	CPOM (gm²)	Ash1 (g)	Ash 2 (g)	Ash 3 (g)	Ash 4 (g)	Ash 5 (g)
TE41	Bobbo 1	Tea	0.6525	1.7067	0.5411	2.3674	0.37266	0.5479	0.5898
TE42	Bappa Saidu 1	Tea	2.7954	2.24056	1.6084	0.7222	1.1001	0.5319	0.6629
TE43	Bapa Zubairu 1	Tea	0.0775	1.55518	0.1035	1.6287	0.6413	0.7956	0.0403
TE44	Mohamadu 1	Tea	2.825	0.99518	0.1045	0.2267	0.1146	0.1237	1.4958
TE45	God free 1	Tea	3.4459	2.55364	2.0922	1.2169	0.5901	0.1807	1.4622
EU46	Yusuf 2	*Eucalyptus*	1.3575	2.70684	2.5437	0.8391	0.7793	1.2333	0.5131
EU47	Alh. Dambi 2	*Eucalyptus*	1.6178	1.95282	0.3349	0.1109	0.2995	1.159	0.3723
EU48	Fragment D	*Eucalyptus*	4.9109	3.5493	0.2795	1.3338	1.4315	0.4257	1.2779
EU49	Alh. Isa 2	*Eucalyptus*	4.5838	2.23548	0.0341	0.1154	0.4603	0.2018	0.3359
EU50	Alh. Yusuf 2	*Eucalyptus*	0.6773	2.31246	1.6566	1.455	2.1521	0.25502	0.289
FR51	Mustapha 1	Fragment	7.9423	3.80228	0.9868	0.4548	0.5054	0.3835	0.4839
FR52	Counsellor 1	Fragment	1.042	1.84218	0.0449	0.068	0.1299	0.2207	1.0424
FR53	Mustapha 2	Fragment	4.6458	6.08372	0.2677	0.4416	0.2359	0.5487	0.3061
FR54	Alh. Umaru	Fragment	1.3874	2.67636	1.8553	0.9692	1.3441	5.0665	2.4808
FR55	Jauro Saidu	Fragment	0.9407	4.44136	4655	0.1543	3.8215	4.0875	2.439

Site ID	Site name	Land use	Elevation(U/S)	% forest	% pasture	Taxa	EPT	Berger Parker	Margalef
CF1	Augustine trans.	Forest	1620	100	0	18	6	0.208791209	6.898814841
CF2	J.S.H 1	Forest	1481	100	0	21	12	0.418719212	7.110741944
CF3	J.S.H 2	Forest	1470	100	0	28	8	0.375661376	9.706602542
CF4	J.S.H 3	Forest	1469	100	0	23	10	0.37654321	8.104130734
CF5	J.S.H 4	Forest	1451	100	0	12	6	0.176470588	4.375932111
CF6	Luga Ginnaji 2	Forest	1564	100	0	8	1	0.384615385	4.323407346
CF7	Luga ginnaji 3	Forest	1550	100	0	27	10	0.224242424	9.54957616
CF8	Luga Ginnaji 1	Forest	1528	100	0	13	6	0.269230769	5.402598678
CF9	Luga Ginnaji 8	Forest	1510	98	2	17	5	0.4	7.259132954
CF10	Luga Ginnaji 9	Forest	1497	98	2	10	6	0.726415094	3.556671429
CF11	Luga Ginnaji 10	Forest	1449	95	5	6	5	0.5	3.027957714
CF12	Luga Ginnaji 6	Forest	1518	95	5	17	5	0.276923077	6.902313564
CF13	Luga Ginnaji 7	Forest	1542	95	5	19	8	0.15942029	7.679183937
CF14	Luga Ginnaji 5	Forest	1523	95	5	15	5	0.163934426	5.402256226
CF15	Luga Ginnaji 4	Forest	1549	96	4	14	5	0.21978022	5.275564291
GR16	Fragment B1	Grassland	1612	100	0	5	1	0.444444444	2.740866514
GR17	Alh. Lawan	Grassland	1580	10	90	11	4	0.7	4.745611564
GR18	Alh. Yusuf 3	Grassland	1586	5	95	17	3	0.498663102	4.735056462
GR19	Alh. Bayero 1	Grassland	1591	3	97	8	2	0.2	4.650699333
GR20	Alh. Bayero 2	Grassland	1596	3	97	12	6	0.2	5.549190149

Site ID	Site name	Land use	Elevation(U/S)	% forest	% pasture	Taxa	EPT	Berger Parker	Margalef
GZ21	Counsellor 3	Grazing	1592	10	90	19	5	0.351851852	7.0905957
GZ22	Counsellor 4	Grazing	1631	20	80	13	4	0.393442623	5.239076952
GZ23	Alh. Dambi 1	Grazing	1611	20	80	11	0	0.344827586	4.090532933
GZ24	Fragment. C	Grazing	1643	10	90	12	5	0.214285714	4.881646683
GZ25	Alh. Kato 2	Grazing	1599	0	100	5	1	0.2	3.321928095
MA26	Fragment A	Maize	1612	100	0	13	4	0.342857143	5.105844109
MA27	Alh. Yusuf 1	Maize	1587	10	90	21	7	0.682092555	6.247059261
MA28	Misa 1	Maize	1603	2	98	10	3	0.31884058	3.839591969
MA29	Misa 2	Maize	1595	2	98	9	3	0.266666667	4.758389113
MA30	Misa 3	Maize	1593	0	100	21	4	0.362745098	7.956240201
CB31	Jacob 1	Cabbage	1594	0	100	7	1	0.48	3.152767363
CB32	Jacob 2	Cabbage	1595	0	100	5	1	0.4	2.657542476
CB33	Ruqaya 1	Cabbage	1601	0	100	14	5	0.379310345	5.059137489
CB34	Ruqaya 2	Cabbage	1612	0	100	10	2	0.388888889	4.365853732
CB35	Habiba K	Cabbage	1632	0	100	7	1	0.75	2.984629224
BA36	Fragment B2	Banana	1642	100	0	6	1	0.25	3.155905737
BA37	Alh. Isa 1	Banana	1636	5	95	6	2	0.516666667	2.189811812
BA38	Mal. Ali	Banana	1621	25	75	6	1	0.627906977	2.049475629
BA39	Head Master	Banana	1638	15	85	10	1	0.25	5.680630326
BA40	Yelwa	Banana	1644	0	100	3	0	0.907524411	0.533910134

Site ID	Site name	Land-use	Elevation(U/S)	% forest	% pasture	Taxa	EPT	Berger Parker	Margalef
TE41	Bobbo 1	Tea	1577	10	90	9	1	0.294117647	3.615459453
TE42	Bapa Saidu 1	Tea	1589	20	80	11	1	0.647058824	4.519324317
TE43	Bapa Zubairu 1	Tea	1598	5	95	8	1	0.444444444	3.614743261
TE44	Mohamadu 1	Tea	1573	2	98	13	3	0.193877551	4.806968077
TE45	God free 1	Tea	1579	20	80	17	4	0.642857143	5.942055969
EU46	Yusuf 2	*Eucalyptus*	1600	10	90	24	6	0.268518519	9.060205616
EU47	Alh. Dambi 2	*Eucalyptus*	1614	5	95	3	0	0.785714286	1.211183085
EU48	Fragment D	*Eucalyptus*	1674	100	0	12	5	0.709897611	3.701189389
EU49	Alh. Isa 2	*Eucalyptus*	1686	100	0	7	0	0.25	4.260637496
EU50	Alh. Yusuf 2	*Eucalyptus*	1587	5	95	8	3	0.409090909	3.788754919
FR51	Mustapha 1	Fragment	1615	0	100	24	6	0.211538462	8.523965722
FR52	Counsellor 1	Fragment	1616	0	100	20	4	0.25	8.127789761
FR53	Mustapha 2	Fragment	1602	0	100	10	5	0.210526316	5.045115725
FR54	Alh. Umaru	Fragment	1616	0	100	20	5	0.326923077	8.554114573
FR55	Jauro Saidu	Fragment	1632	0	100	19	5	0.210526316	7.960991728

Appendix 2: Summary of invertebrates for 55 streams surveyed between October 2009 and March 2010 on Mambilla Plateau Nigeria used in this study. Numbers indicate total density for 5 surber samples, and x represents species present in a kick net sample.

Stream ID - Land use	**CF1**	**CF2**	**CF3**	**CF4**	**CF5**	**CF6**	**CF7**	**CF8**	**CF9**	**CF10**	**CF11**
Odonata											
Gomphidae		1		4		1	1		5		
Libellulidae											
Macromiidae				x				x			
Aeshnidae								1	1	1	2
Calopterygidae											
Zygoptera											
Ephemeroptera											
Ephemeridae									x	1	
Leptophlebiidae sp. A	4	9	12	4	12		5	7	x		9
Leptophlebiidae sp. B											x
Leptophlebiidae sp. C											
Siphloneuridae	3										
Oligoneuridae	x	x	x	2	2					2	
Baetidae sp. A	18	10	8	20	23	4	4	8	2	4	3
Baetidae sp. B		x					7				
Caenidae	2	2		1	1	1	x	1	x	2	
Heptagenidae		4									
Plecoptera											
Perlidae	x	1	7	3	2		5	1	1	x	2
Perlidae sp. B			1	2			3				
Phanoperla	2										

Stream ID - Land use	CF1	CF2	CF3	CF4	CF5	CF6	CF7	CF8	CF9	CF10	CF11
Trichoptera											
Leptoceridae sp A			1					1			
Leptoceridae sp. B											
Hydropsychidae sp. A		4	11		18			3	1		1
Hydropsychidae sp. B	x	x	x	9	x	x					x
Polycentropodidae											
Limnephilidae											
Limnephilus											
Lepidostomotidae	1	1	3	7	7		10	1	1		
Philopotamidae							1				1
Sericostomatidae											
Psychomyiidae	x			1							
Glossomatidae											
Coleoptera											
Ptylodactylidae						x					
Hydrophilidae						1					
Dysticidae					3	x	1		2		
Scirtidae sp. A	6			x	x	x	1				
Scirtidae sp. B					2						
Elmidae sp. A	3	3		2	2	x	x	4			2
Elmidae sp. B		1	2	1							
Elmidae sp. C											
Elmidae sp. D											
Gyrinidae	1			x		x	1	1			x
Staphylinidae	1		x		3						
Psephenidae							1				

Stream ID - Land use	CF1	CF2	CF3	CF4	CF5	CF6	CF7	CF8	CF9	CF10	CF11
Diptera											
Ceratopogonidae	x	15	3	x	2						1
Chironomidae	x	85	71	10	17	3	1	6	4	1	13
Tanyderidae	4	x	x	x	x	x	1	x	21	x	x
Tanypodinae	1	6	4	19		2		8			
Chironominae				61							
Empididae	16		1			2	3				
Tipulidae	1	5	7	5	7	x	7	2	3	1	10
Limonia				1			1				
Muscidae					x	1		1			
Simulidae	x	1		3			1	x		1	x
Dixidae											
Syrphidae								1			
Arthericidae	7		2	1	x						
Psychodidae			1					x			x
Diptera											
Hemiptera											
Naucordiae											
Belostoma											
Notonectidae						x					
Gerridae	1	x				2					
Nepidae										x	
Mesovillidae		1				x			4		x
Veliidae		x	x			1			2	77	3
Corixidae											

Stream ID - Land use	**CF1**	**CF2**	**CF3**	**CF4**	**CF5**	**CF6**	**CF7**	**CF8**	**CF9**	**CF10**	**CF11**
Mollusca											
Ostracod			7					1			
Crustacea											
Atyidae (shrimp)								14			
Brachyura (crab)	x		1	2	4		1		1	1	x
Oligochaeta		x							x		
Lumbriculidae		3						2			
Platyhelminthes			3				1				
Leech											
Collembola	x		2		1						
Acari											
Spider		1	1		2						1
Blattodae			1								
Chordata											
Xenopus tropicalis	5					3	8		3	x	2
Tilapia zilli	2			1	1						
Total taxa	**78**	**153**	**149**	**159**	**109**	**21**	**64**	**63**	**51**	**91**	**50**

Stream ID - Land use	CF12	CF13	CF14	CF15	GR16	GR17	GR18	GR19	GR20	GZ21	GZ22
Odonata											
Gomphidae	1	1	1		1	1		2			
Libellulidae		1	2						x		
Macromiidae											
Aeshnidae											
Calopterygidae						x					
Zygoptera						1					
Ephemeroptera											
Ephemeridae									x	x	x
Leptophlebiidae sp. A	X	4	5	1			1		2	1	1
Leptophlebiidae sp. B	X						3				
Leptophlebiidae sp. C	x						1				x
Siphloneuridae			6								
Oligoneuridae		5	x	7			x		x		1
Baetidae sp. A	x	6	18	19			17	x		x	
Baetidae sp. B				1							
Caenidae	x	1		1			1				
Heptagenidae											
Plecoptera											
Perlidae	x	5	9	4			6				
Perlidae sp. B											
Phanoperla											

Stream ID - Land use	CF12	CF13	CF14	CF15	GR16	GR17	GR18	GR19	GR20	GZ21	GZ22
Trichoptera											
Leptoceridae sp A	4				x		x	2	x	x	
Leptoceridae sp. B		x			4		2		2		
Hydropsychidae sp. A		3	x			4	8		x	25	x
Hydropsychidae sp. B		1					3		2		6
Polycentropodidae			1							x	
Limnephilidae											
Limnephilus											
Lepidostomotidae	x	x	1				7	1	2	3	6
Philopotamidae	x						1				
Sericostomatidae											
Psychomyiidae				1						1	
Glossomatidae	x										
Coleoptera											
Ptylodactylidae							3				x
Hydrophilidae		2				x			x		
Dysticidae	x		1	2			x	x		x	
Scirtidae sp. A	x		x	2	x	1	2			x	
Scirtidae sp. B			14								
Elmidae sp. A	x	x				1	x		x		
Elmidae sp. B											
Elmidae sp. C				x							
Elmidae sp. D											
Gyrinidae	1	2			1	x	1				
Staphylinidae											
Psephenidae											

Stream ID - Land use	CF12	CF13	CF14	CF15	GR16	GR17	GR18	GR19	GR20	GZ21	GZ22
Diptera											
Ceratopogonidae	2		x				2		1	x	
Chironomidae	1	2	54	17	3	1	373	1	3	x	17
Tanyderidae	x		x	19		x			x	x	
Tanypodinae			7			7	4		4		
Chironominae								3			
Empididae											
Tipulidae	x	4	6	6		1	x	1	3	x	
Limonia						x					
Muscidae											
Simulidae				6						x	
Dixidae	x									x	
Syrphidae											
Arthericidae		1									
Psychodidae			1								
Diptera											
Hemiptera											
Naucordiae										x	
Belostoma											
Notonectidae								x			
Gerridae			1	3						x	
Nepidae											
Mesovillidae											
Veliidae	x		1								16
Corixidae							x	x		x	

Stream ID - Land use	**CF12**	**CF13**	**CF14**	**CF15**	**GR16**	**GR17**	**GR18**	**GR19**	**GR20**	**GZ21**	**GZ22**
Mollusca											
Ostracod			1								
Crustacea											
Atyidae (shrimp)						1					
Brachyura (crab)		2								x	
Oligochaeta											
Lumbriculidae		1									x
Platyhelminthes											
Leech				x						x	
Collembola				1							
Acari											
Spider		1									
Blattodae											
Chordata											
Xenopus tropicalis	x		10				1				
Tilapia zilli						1			2		1
Total taxa	**9**	**42**	**139**	**90**	**9**	**19**	**436**	**10**	**21**	**30**	**48**

Stream ID - Land use	GZ23	GZ24	GZ25	MA26	MA27	MA28	MA29	MA30	CB31	CB32	CB33
Odonata							0	0			
Gomphidae	1	x	x	2				x	1	3	1
Libellulidae				1		x	x			1	
Macromiidae											
Aeshnidae	1	3								1	
Calopterygidae											
Zygoptera											
Ephemeroptera											
Ephemeridae											
Leptophlebiidae sp. A		x		9	3	x					x
Leptophlebiidae sp. B					5						
Leptophlebiidae sp. C											4
Siphloneuridae				9							1
Oligoneuridae				x							x
Baetidae sp. A				22							x
Baetidae sp. B											x
Caenidae								x			
Heptagenidae											
Plecoptera											
Perlidae				2							
Perlidae sp. B											
Phanoperla										1	1

Stream ID - Land use	GZ23	GZ24	GZ25	MA26	MA27	MA28	MA29	MA30	CB31	CB32	CB33
Trichoptera											
Leptoceridae sp A		x			4					1	10
Leptoceridae sp. B					8						x
Hydropsychidae sp. A		x		19	x						x
Hydropsychidae sp. B		14			101						
Polycentropodidae											1
Limnephilidae											
Limnephilus											2
Lepidostomotidae		6			4	x					x
Philopotamidae					1						x
Sericostomatidae											
Psychomyiidae					1						
Glossomatidae											
Coleoptera											
Ptylodactylidae		2							7		7
Hydrophilidae	1		x		2						
Dysticidae		x		x	5		x	x	x		x
Scirtidae sp. A		1	1	1	1	x					
Scirtidae sp. B					2						
Elmidae sp. A					7						
Elmidae sp. B				2	1						
Elmidae sp. C											
Elmidae sp. D											
Gyrinidae					1						
Staphylinidae					x						
Psephenidae											

Stream ID - Land use	GZ23	GZ24	GZ25	MA26	MA27	MA28	MA29	MA30	CB31	CB32	CB33
Diptera										4	44
Ceratopogonidae		1									x
Chironomidae		x	4	x	43	x		x	1	1	2
Tanyderidae			1		10	x	x	x	x		
Tanypodinae			1		10						
Chironominae				2							2
Empididae											1
Tipulidae	x	4	2	5	2	x	x				x
Limonia											
Muscidae											
Simulidae				1	2						
Dixidae											
Syrphidae											
Arthericidae											
Psychodidae											
Diptera											
Hemiptera											
Naucordiae											x
Belostoma				1							
Notonectidae		1									
Gerridae											
Nepidae											
Mesovillidae									3		
Veliidae	1				9			x	x		
Corixidae		2							x		

Stream ID - Land use	**GZ23**	**GZ24**	**GZ25**	**MA26**	**MA27**	**MA28**	**MA29**	**MA30**	**CB31**	**CB32**	**CB33**
Mollusca											
Ostracod											
Crustacea											
Atyidae (shrimp)											
Brachyura (crab)		1		1	5						
Oligochaeta											
Lumbriculidae											
Platyhelminthes											
Leech											
Collembola									1		
Acari											
Spider		1									
Blattodae											
Chordata											
Xenopus tropicalis				1							
Tilapia zilli					1						
Total taxa	**4**	**36**	**8**	**78**	**218**	**0**	**0**	**0**	**13**	**12**	**80**

Stream ID - Land use	CB34	CB35	BA36	BA37	BA38	BA39	BA40	TE41	TE42	TE43	TE44
Odonata											
Gomphidae	1	x		x					1		x
Libellulidae			2			4				2	3
Macromiidae											
Aeshnidae			2			1		2	1	x	3
Calopterygidae											
Zygoptera		x				x	x			1	
Ephemeroptera											
Ephemeridae											
Leptophlebiidae sp. A				x							
Leptophlebiidae sp. B											
Leptophlebiidae sp. C		1		1						1	
Siphloneuridae											
Oligoneuridae				x		1					
Baetidae sp. A						x					
Baetidae sp. B						x					
Caenidae											
Heptagenidae											
Plecoptera											
Perlidae											
Perlidae sp. B											
Phanoperla											

Stream ID - Land use	CB34	CB35	BA36	BA37	BA38	BA39	BA40	TE41	TE42	TE43	TE44
Trichoptera											
Leptoceridae sp A	3		1							x	x
Leptoceridae sp. B		1		1	1	x					
Hydropsychidae sp. A	x			x	x						x
Hydropsychidae sp. B											
Polycentropodidae		15		15							
Limnephilidae											
Limnephilus	5										
Lepidostomotidae				x							
Philopotamidae	x	1		1				2	1		
Sericostomatidae											
Psychomyiidae				x				x	x		
Glossomatidae											
Coleoptera					1						4
Ptylodactylidae	5								1		
Hydrophilidae		1		1	x			1			x
Dysticidae	x	x			x				x	x	
Scirtidae sp. A											
Scirtidae sp. B										x	
Elmidae sp. A											
Elmidae sp. B											
Elmidae sp. C			2								1
Elmidae sp. D											
Gyrinidae											
Staphylinidae	x					x					x
Psephenidae											

Stream ID - Land use	**CB34**	**CB35**	**BA36**	**BA37**	**BA38**	**BA39**	**BA40**	**TE41**	**TE42**	**TE43**	**TE44**
Diptera											
Ceratopogonidae		3		3	55				6	1	18
Chironomidae	2	x		x	1	x	x		x	1	16
Tanyderidae	10						17				
Tanypodinae											
Chironominae			3			1		6	4	2	
Empididae											
Tipulidae			x	x		x		x	x		
Limonia											
Muscidae											
Simulidae	1										
Dixidae											
Syrphidae											
Arthericidae											
Psychodidae											
Diptera											
Hemiptera			3					2	3		1
Naucordiae			x								
Belostoma							1	x	x		x
Notonectidae											
Gerridae					3		x				1
Nepidae	1	2		2		1		1	1	2	1
Mesovillidae	1				1						
Veliidae	x			x		x			x	x	
Corixidae	x				x						

Stream ID - Land use	**CB34**	**CB35**	**BA36**	**BA37**	**BA38**	**BA39**	**BA40**	**TE41**	**TE42**	**TE43**	**TE44**
Mollusca											
Ostracod											
Crustacea											
Atyidae (shrimp)											
Brachyura (crab)									x		1
Oligochaeta											
Lumbriculidae							1				
Platyhelminthes											1
Leech			1				x		1		
Collembola								1	1		
Acari			x						2		
Spider											
Blattodae						1				2	
Chordata											
Xenopus tropicalis						x					
Tilapia zilli											
Total taxa	**30**	**25**	**16**	**25**	**62**	**10**	**19**	**15**	**30**	**15**	**61**

Stream ID - Land use	TE45	EU46	EU47	EU48	EU49	EU50	FFR51	FFR52	FFR53	FFR54	FFR55
Odonata			0								
Gomphidae	3	x	x	2					x	3	
Libellulidae	3				2	x		3			2
Macromiidae											
Aeshnidae		1					1				
Calopterygidae											
Zygoptera											
Ephemeroptera											
Ephemeridae											x
Leptophlebiidae sp. A							9				
Leptophlebiidae sp. B											
Leptophlebiidae sp. C							3				
Siphloneuridae								1		3	
Oligoneuridae	3										
Baetidae sp. A							x	1			
Baetidae sp. B							1	x		x	
Caenidae	x							x			
Heptagenidae											
Plecoptera											
Perlidae							x				
Perlidae sp. B											
Phanoperla										1	

Stream ID - Land use	**TE45**	**EU46**	**EU47**	**EU48**	**EU49**	**EU50**	**FFR51**	**FFR52**	**FFR53**	**FFR54**	**FFR55**
Trichoptera	1										
Leptoceridae sp A			x	12		3	10	5		11	
Leptoceridae sp. B	20					3	5			1	
Hydropsychidae sp. A	x			x		x	x	x		x	
Hydropsychidae sp. B											
Polycentropodidae		1		1			1	1	1	6	
Limnephilidae											
Limnephilus	2										
Lepidostomotidae	1	x		x			x	x	x	x	
Philopotamidae											
Sericostomatidae											
Psychomyiidae											
Glossomatidae											
Coleoptera	1			1					4		
Ptylodactylidae					2		3		2	2	
Hydrophilidae	6	x	x	3		x	15		x	x	
Dysticidae		x			x		x		x	x	
Scirtidae sp. A	x	x		1		2	x	1		2	
Scirtidae sp. B							8	2			
Elmidae sp. A							x				
Elmidae sp. B											
Elmidae sp. C										3	
Elmidae sp. D				x		1	6				
Gyrinidae						x	x				
Staphylinidae											
Psephenidae											

Stream ID - Land use	**TE45**	**EU46**	**EU47**	**EU48**	**EU49**	**EU50**	**FFR51**	**FFR52**	**FFR53**	**FFR54**	**FFR55**
Diptera	103			201	1	13	3	1		1	
Ceratopogonidae				x				1			
Chironomidae	5	x		51	x	x	2	1		x	
Tanyderidae		3						x			1
Tanypodinae	x	x		x		x	x	x	x	2	
Chironominae	3			1			2	3	1	1	1
Empididae											
Tipulidae	x			x			x	x	x	x	x
Limonia	1						2	1		2	
Muscidae											
Simulidae	x						x	x		x	
Dixidae											
Syrphidae											
Arthericidae											
Psychodidae											
Diptera											
Hemiptera	6	1									
Naucordiae	x					x	x				x
Belostoma	x			1		x	x				x
Notonectidae					x						
Gerridae					1	x	1				1
Nepidae				1			7	1			2
Mesovillidae					x	1					1
Veliidae			x				x	x			
Corixidae			x			x					

Stream ID - Land use	TE45	EU46	EU47	EU48	EU49	EU50	FFR51	FFR52	FFR53	FFR54	FFR55
Mollusca											
Ostracod							32	27	1		
Crustacea							2	1			1
Atyidae (shrimp)							x	x			
Brachyura (crab)							x	x		1	
Oligochaeta											
Lumbriculidae										x	
Platyhelminthes	1									1	1
Leech	1				1						
Collembola	2			1			2				
Acari	x				x					x	x
Spider											
Blattodae							1			1	
Chordata											
Xenopus tropicalis		2								x	
Tilapia zilli											
Total taxa	**166**	**8**	**0**	**276**	**8**	**23**	**117**	**51**	**9**	**41**	**11**

Appendix 3: Mean taxa (± SE per 0.09 m^2) stream benthic invertebrates sampled at the study sites between October 2009 and March 2010 on the Mambilla Plateau. Land use groups: Crops & pasture, N = 20; Plantation, N = 15; Forest fragments, N = 5 and Cont. forest, N = 5, - = absent.

Taxa	Crops & pasture	Plantation	Forest fragment	Cont. forest
Odonata				
Gomphidae	1.0 ± 0.4	1.0 ± 0.4	1.0 ± 0.8	2.0 ± 0.6
Libellulidae	1.0 ± 0.4	1.3 ± 0.5	3.0 ± 2.4	2.0 ± 0.5
Aeshnidae	0.6 ± 0.5	2.0 ± 0.7	3.0 ±3.0	1.3 ± 0.3
Macromiidae	1.0 ± 0.6	2.0 ± 0.2	1.0 ± 0.8	2.0 ± 0.2
Ephemeroptera				
Calopterygidae	0.5 ± 0.3	0.5 ± 0.4	1.0 ± 0.8	2.0 ± 0.2
Ephemeridae	0.5 ± 0.5	0.3 ± 0.3	1.0 ± 0.8	1.0 ± 0.8
Leptophlebiidae sp.A	0.4 ± 0.4	-	1.0 ± 0.8	7.0 ± 1.1
Leptophlebiidae sp.B	0.8 ± 0.5	-	9.0 ± 7.2	2.0 ± 0.2
Leptophlebiidae sp.C	2.0 ± 0.9	-	2.0 ± 0.2	2.0± 0.2
Siphloneuridae	1.3 ± 0.5	0.3 ± 0.4	3.0 ± 2.4	5.0 ± 2.0
Oligoneuridae	0.5 ± 0.5	0.3 ± 0.3	2.0 ± 3.0	4.0 ± 1.0
Baetidae sp.A	5.3 ± 4.0	1.0 ± 0.8	5.3 ± 4.0	11.0 ± 2.0
Baetidae sp.B	0.5 ± 0.5	0.3 ± 0.3	1.0 ± 0.8	4.0 ± 3.0
Caenidae	2.0 ± 2.0	-	1.0 ± 0.8	1.3 ± 0.2
Heptagenidae	0.5 ± 0.5	-	0.5 ± 0.5	4.0 ± 3.0
Plecoptera				
Perlidae	2.0 ± 2.0	-	0.5 ± 0.5	4.0 ± 0.8
Perlidae sp.B	0.5 ± 0.5	-	0.8 ± 0.5	2.0 ± 0.6
Phanoperla	0.8 ± 0.5	-	0.8 ± 0.5	2.0 ± .1.0
Trichoptera				
Leptoceridae sp. A	2.0 ± 1.0	-	1.0 ± 0.8	2.0 ± 1.0
Leptoceridae sp.B	0.7 ± 0.7	3.0 ± 2.0	9.0 ± 1.0	9.0 ± 1.0
Hydropsychidae sp. A	-	8.0 ± 5.0	3.0 ± 5.0	6.0 ± 2.4
Hydropsychidae sp. B	7.0 ± 6.1	0.3 ± 0.3	-	-
Polycentropodidae	4.0 ± 2.0	-	-	1.0 ± 0.8

Limnephilidae (*Limnephilus*)	2.0 ± 2.0	0.3 ± 0.3	2.0 ± 0.2	2.0 ± 2.0
Lepidostomatidae	2.2 ± 1.4	6.0 ± 4.0	-	4.0 ± 1.2
Philopotamidae	7.0 ± 5.0	0.3 ± 0.3	-	1.0 ± 0.8
Sericostomatidae	0.5 ± 0.5	0.5 ± 0.5	-	1.5 ± 0.2
Psychomyiidae	0.5 ± 0.5	0.3 ± 0.3	-	1.0 ± 0.8
Glossosomatidae	2.0 ± 0.6	-	2.0 ± 0.2	2.0 ± 0.2
Coleoptera				
Ptylodactylidae	2.0 ± 1.1	-	-	-
Hydrophilidae	1.0 ± 0.6	1.0 ± 0.5	3.0 ± 3.0	2.0 ± 0.5
Dysticidae	0.8 ± 0.5	2.2 ± 0.9	15.0 ± 12.0	2.0 ± 0.4
Scirtidae sp.A	0.4 ± 0.4	0.3 ± 0.3	-	3 ± 2.0
Scirtidae sp.B	5.3 ± 4.3	0.5 ± 0.4	2.0 ± 2.0	8.0 ± 6.0
Elmidae sp. A	6.0 ± 5.4	-	5.0 ± 8.0	3.0 ± 0.3
Elmidae sp. B	0.5 ± 0.5	-	-	1.3 ± 0.3
Elmidae sp.C	0.5 ± 0.5	-	2.0 ± 0.2	2.0 ± 0.2
Elmidae sp.D	0.5 ± 0.5	0.3 ± 0.3	3.0 ± 5.0	2.0 ± 0.2
Gyrinidae	0.3 ± 0.3	1.0 ± 0.5	6.0 ± 5.0	1.2 ± 0.2
Staphylinidae	0.1 ± 0.1	-	0.1 ± 0.1	2.0 ± 1.0
Psephenidae	0.5 ± 0.5	-	0.4 ± 0.4	1.0 ± 0.8
Diptera				
Ceratopogonidae	0.4 ± 0.4	-	0.1 ± 0.1	5.0 ± 3.0
Chironomidae	20.0 ± 19.0	20.4 ± 8.0	1.0 ± 0.8	-
Tanyderidae	7.3 ± 4.0	19.4 ± 13.0	2.0 ± 2.0	11.3 ± 5.1
Empididae	0.5 ± 0.5	2.0 ± 0.9	2.0 ± 3.0	6.0 ± 4.0
Tipulidae	0.4 ± 0.4	0.3 ± 0.3	0.4 ± 0.4	5.0 ± 0.7
Limonia	1.3 ± 0.8	-	0.4 ± 0.4	1.0 ± 0.8
Muscidae	0.5 ± 0.5	0.3 ± 0.3	2.0 ± 2.0	1.0 ± 0.8
Simulidae	0.8 ± 0.5	-	-	2.4 ± 1.0
Dixidae	0.5 ± 0.5	-	-	-

Syrphidae	0.5 ± 0.6	-	-	1.0 ± 0.8
Athericidae	0.5 ± 0.7	-	-	3.0 ± 1.4
Psychodidae	0.5 ± 0.8	-	-	1.0 ± 0.8
Megaloptera				
Sialidae	0.5 ± 0.9	-	-	1.0 ± 0.8
Hemiptera				
Naucordiae	0.5 ± 0.1	-	-	-
Belostoma	0.5 ± 0.1	-	-	-
Notonectidae	0.5 ± 0.1	-	-	-
Gerridae	0.5 ± 0.1	-	-	-
Nepidae	0.8 ± 0.5	-	-	2.0 ± 0.5
Mesoveliidae	0.8 ± 0.5	-	1.0 ± 0.8	1.0 ± 0.8
Veliidae	0.8 ± 0.5	2	3.3 ± 7.0	3.0 ± 2.0
Corixidae	0.5 ± 0.5	1.0 ± 0.5	1.0 ± 0.8	17.0 ± 15.1
Collembola	0.5 ± 0.5	-	-	2.0 ± 1.0
Gastropoda				
Melanoides tuberculatus	3.0 ± 2.0	1.0 ± 0.6	3.0 ± 2.0	1.0 ± 0.6
Bulinus globosus	1.0 ± 0.5	1.0 ± 0.6	1.0 ± 0.6	1.0 ± 0.6
Crustacea				
Ostracoda	0.5 ± 0.5	-	-	5.0 ± 4.0
Atyidae	0.5 ± 0.5	-	-	3.0 ± 2.0
Brachyura	0.3 ± 0.3	-	30.0 ± 27.0	14.0 ± 13.1
Annelida				
Lumbriculidae	0.5 ± 0.5	-	-	1.7 ± 0.4
Hirudinea	0.8 ± 0.8	0.3 ± 0.3	1.0 ± 0.8	2.0 ± 1.0
Insecta				
Acari	0.5 ± 0.5	-	-	1.3 ± 0.3
Araneae	0.5 ± 0.5	-	2.0 ± 1.0	2.0 ± 1.0
Blattodea	0.5 ± 0.5	0.6 ± 0.5	-	1.2 ± 0.2

Chordata				
Xenopus tropicalis	1.0 ± 0.4	-	-	1.0 ± 0.8
Tilapia zilli	0.4 ± 0.4	0.7 ± 0.5	1.0 ± 0.8	5.2 ± 1.3

Appendix 4: Density of consumers mostly collected from stones and wood from the 9 study streams on the Mambilla Plateau. Abbreviations are those used for food webs in Fig. 1. - = animals that were not collected from stones/wood. Consumer species used for analyses of gut contents and stable isotope signatures (indicated by *) are shown in the last two columns. Numbers in parentheses indicate number of size groups.

Family/higher taxon	Taxa	Density range (no/m^2)	Guts	Isotopes
DECAPODA				
Astacidae	Astacidae			
Atydae	*Caridina*			
Potamonautidae	Potamonautidae	-	*(1)	*(1)
EPHEMEROPTERA				
Baetidae	*Baetis* sp.			
Caenidae	Caenidae			
Heptageniidae	Heptageniidae			
Leptophlebiidae	Leptophlebiidae			
Oligoneuriidae	*Elassoneuria*	15–60	*(3)	*(3)
ODONATA				
Aeshnidae	Aeshnidae	1–2		
Calopterygidae	Calopterygidae			
Coenagrionidae				
Corduliidae	Corduliidae	0.0–0.6		
Gomphidae	Gomphidae	0–2	*(3)	*(3)
Lestidae				
Libellulidae	Libellulidae	0.2–0.7		
PLECOPTERA				
Perlidae	*Neoperla*	3–8	*(3)	*(3)
HEMIPTERA				
Belostomatidae	*Belostoma*			
Corixidae	*Corixa*			
Gelastocoridae				
Gerridae				
Hydrometridae	*Hydrometra*			
Mesovillidae				
Naucoridae				

Nepidae					
Notonectidae					
Veliidae	*Rhagovelia*				
TRICHOPTERA					
Brachycentridae					
Glossosomatidae					
Hydropsychidae	Sp. A	4–10		*(3)	*(3)
Lepidostomatidae					
Leptoceridae					
Philopotamidae					
Polycentropodidae	*Polycentropus* sp.				
Psychomyiidae					
Sericostomatidae					
COLEOPTERA		CO			
Hydraenidae		Hdr			
Hydrophilidae	*Deralus*	Hdp			
Dysticidae	*Cope latus* sp.	Dys			
Dysticidae	sp. A				
Dysticidae	sp. B				
Scirtidae	sp. A	Sci			
Scirtidae	sp. B				
Elmidae	sp. A	Elm			
Elmidae	sp. B				
Elmidae	Sp. C				
Elmidae	Sp. D				
Gyrinidae	*Dineutus*	Gyr	-	*(3)	*(3)
Gyrinidae	*Orectochilus*		-	*(3)	*(3)
Staphylinidae		Sta			
Chrysomelidae	*Agasicles hygrophila*	Chr			
Psephenidae		Pse			

DIPTERA		DI			
Ceratopogonidae	Ceratopogonidae	Cer			
Chironomidae	Chironominae	Chn			
Chironomidae	*Chironomus*				
Chironomidae	Tanypodinae				
Empididae	Empididae	Emp			
Stratiomiidae		Str			
Tipulidae	*Leptotarsus*	Tip	-	*(3)	*(3)
Tipulidae	*Hexatomini* (*Limonia*)				
Simulidae	*Simulium*	S			
Dixidae	Dixidae	D			
Syrphidae	Syrphidae	Syr			
Athericidae	Arthericidae	Art			
Athericidae	Arthericidae				
Culicidae		Cu			
TRICLADIDA		TD			
Hirudinea	Leech	Lee			
ANNELIDA		AN			
Naididae	Naididae	Tub			
GASTROPODA		GA			
Thiaridae	*Melanoides tuberculatus*	Mel	1–3	*(2)	*(2)
Planorbidae	*Bulinus globosus*	Bul	5–15	*(2)	*(2)
RANATRA	*Xenopus tropicalis*	Xen	-	*(3)	*(3)
PISCES		PCS			
Cichlidae	*Tilapia zilli*	Til	-	*(2)	*(1)
Cichlidae	*Oreochromis niloticus*	Ore	-	*(2)	*(1)
Clariidae	*Clarias lazera*	Cla	-	*(2)	*(1)

Appendix 5: Reprint of article published derived from chapter two; study on the effects of light traps on dragonflies on Mambilla Plateau.

Umar, **D**. **M**., Marinov, M. G., Schorr, M. and Chapman, H. M. (2012) Odonata attracted by light – a new topic for myth-busters. *International Dragonfly Fund-Report*, **43**, 1–52.

Appendix 6: Reprint of article published derived from chapter three; an application of the maximum convex sum algorithm in determining environmental variables that affect Nigerian highland stream benthic communities.

Thaher, M., **Umar**, **D**., Takaoka, T. and Harding, J. (2013) Application of the maximum convex sum algorithm in determining environmental variables that affect Nigerian highland stream benthic communities. *Procedia Computer Science*, **18,** 908–918. DOI: http://dx.doi.org/10.1016/j.procs

Odonata attracted by light – a new topic for myth-busters

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Abstract

Six Odonata species were collected during night light trapping on the Mambilla Plateau, Taraba State Nigeria. Being predominantly diurnal insects, odonates captured in light traps have always been considered as an anomaly. The new data initiated an extensive interrogation of all records on Odonata collected near artificial light sources. A total of 415 records (402 published and 13 new) are presented here with a summary of previous discussions and new discussion points. The general conclusion is that odonates are mainly confused by, rather than attracted to the light. New avenues for further research in this field are suggested based on previous important studies undertaken on Odonata morphology and physiology.

Introduction

Odonates are amongst the oldest of distinct insect orders and supremely visual animals (Yang & Osorio 1996). They have the largest compound eyes of any insect and the highest number of omatidia (Corbet 1999). As a result it is not surprising that their vision has evolved to near perfection. Olberg et al. (2005) proved that odonates, perched or flying, could precisely estimate the size of their potential prey and the distance to it. Moreover they can aim at a point in front of their prey, so that it is intercepted with a relatively straight flight trajectory. Mizutani et al. (2003) report on the so called motion camouflage established in *Anax papuensis* (Burmeister, 1839) and possibly used by other species as well. This is achieved when the predator moves towards the prey in such a manner that projects a stationary image in the prey's retina. This aerial manoeuvre involves a precise estimation of prey's position and movements.

Visual clues play a crucial role in prey detection by Odonata (Labhart & Nilsson 1995, Olberg et al. 2000, 2005), as well as in habitat selection (Wildermuth 1994), sexual recognition behaviour (Wildermuth 1998) and any aspects of pre- and postcopulatory behaviour (Corbet 1999). Moreover several studies support the suggestion that the

polarised light reflected by water provides important information on the quality of freshwater habitats, not only for odonates, but for number of aquatic insects (Kriska et al. 2006). These authors found that red and black horizontal plastic reflector sheets were equally highly attractive to water insects, while yellow and white reflectors were unattractive. In odonates reflective surfaces can aid the orientation from a distance, particularly where other cues (e.g. atmospheric humidity, dimension and shape of the water body, undulation of the water surface, water plants on the surface and on the shore, temperature and odour) are still ineffective (Bernáth et al. 2002).

In spite of their visual superiority odonates have often been confused and trapped when their natural environment has been altered by humans. Individuals have been reportedly attracted by the shiny surface of car roofs (Wildermuth & Horváth 2005), asphalt (Fraser 1936), solar panels (Horváth et al. 2010), and grave stones (Horváth et al. 2007). Furthermore, choice experiments have shown that crude oil can be more attractive to odonates than water (Horváth et al. 1998). Therefore, odonates have been sampled with various traps usually set up for studies on other animal groups. Aerial nets attached to large vessels have produced interesting findings on the migratory species (Holzapfel & Harrell 1968, Wolf et al. 1986, Yoshimoto et al. 1962), as have ornithological and bow nets (Baccetti et all. 1990; Borisov 2008, 2009; Rintele 1997). Hoess & Rezbanyai-Reser (2005) caught the powerful flier *Libelulla quadrimaculata* Linnaeus, 1758 with a pitfall trap. Although very rare, Odonata in pitfall traps have been reported in other occasions, too (Garcia Ruiz 2005, Mertent et al. 2007, Santos et al. 2007). Dogramaci et al. (2010) collected Zygoptera specimens using pan traps and on several occasions odonates have been collected with Malaise traps (Askew et al. 1998; Flint 1996, Richards & Windsor, 2007; Rizali et al. 2002, Sartor et al. 2009). Glotzhober & Riggs (1998) were able to increase their total catch of Odonata using a modified Malaise trap.

However, the majority of records of trapped Odonata come from collections around light sources. The total catch per trap varies between regions globally but range from single individuals to tens of thousands (Feng et al. 2006). There are conflicting views about the reasons behind this relatively high trapping success at night. Odonates are predominantly diurnal species, but the significant number collected near light sources has led many researchers to interpret this behaviour as some kind of attraction to the light (e.g. Aubert 1964; Averill 1995).

Odonata larvae have also been collected using underwater light-traps (Aiken 1979, Dommanget 1991, Engelmann 1973, 1974, Espinosa & Clark 1972, Hungerford et al. 1955, Nikolaeva 2008, Schilling et al. 2009, Weber 1987, Williams et al. 1996). Some laboratory studies on the orientation of the larvae according to the light rays have been undertaken as well (Abbott 1926, Riley 1912).

The present paper presents new data on odonates captured from light traps. It investigates the previous records of all Odonata collected by light sources, presents a

discussion on the probable reasons for this behaviour and suggests future research to clarify this behaviour.

Material and Methods

Light trapping was conducted on the Mambilla Plateau (approx. 1,500 m a.s.l.) near the village of Yelwa, Taraba State, Nigeria (Fig. 1). The trapping was a part of a larger ecological study investigating the effect of land use on benthic invertebrate communities in tropical highland Nigerian streams. Nine streams were selected in three differing land uses: three forested, three maize fields and three tea plantations (Fig. 1 and Table 1). The traps consisted of a light source (12 volts DC flash lamps) and a white plastic tray filled with water. Detergent was added to the water to reduce surface tension.

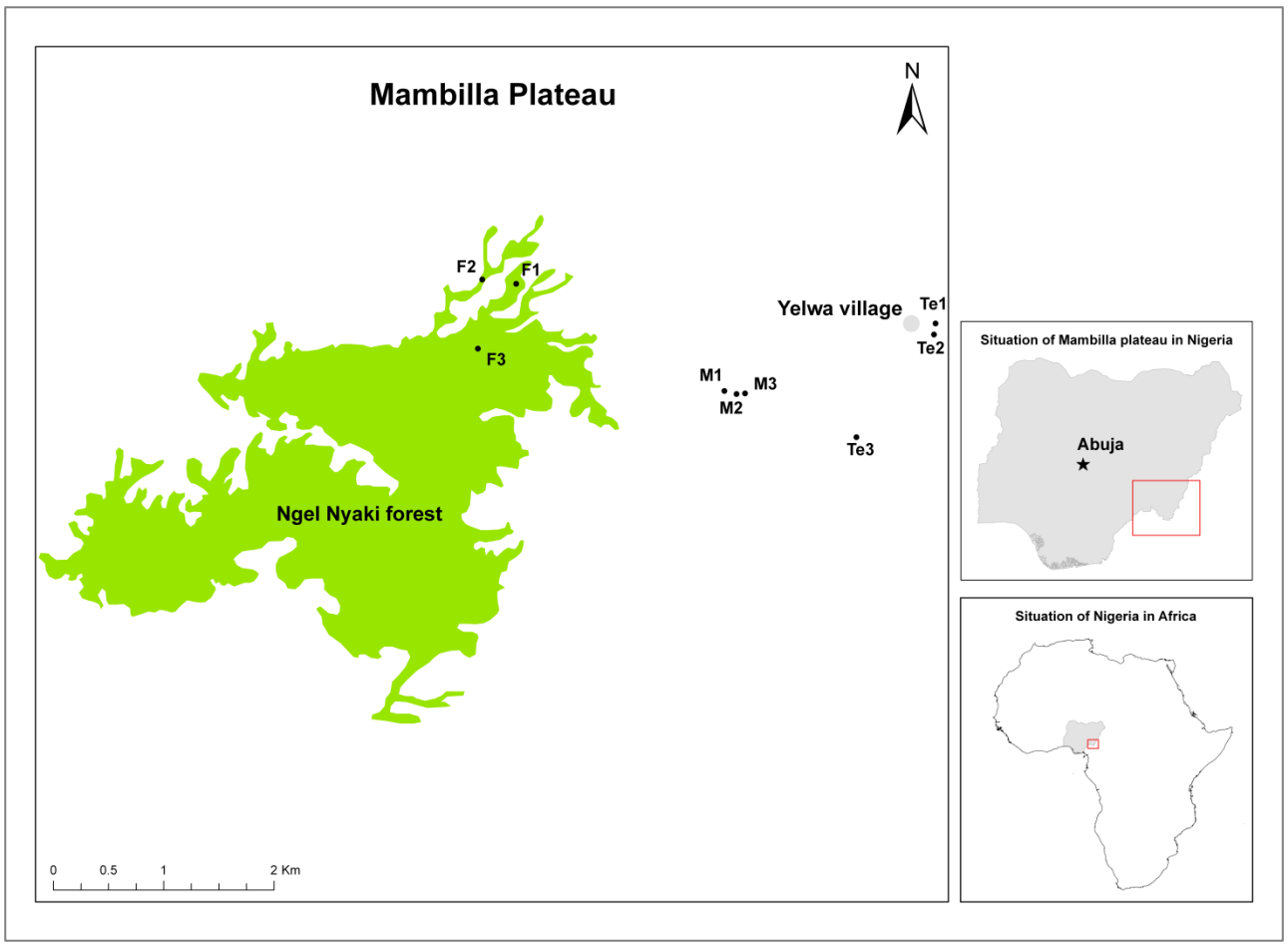

Figure 1. Situation of light traps on Mambilla Plateau, Taraba State Nigeria.

The trays were placed at about 30cm from the water edge and the light source was attached at about 30cm above the trays' rim (Fig. 2). Light traps were set up overnight in four occasions (07 December 2010, 07 January 2011, 07 February 2011 and 07 March 2011). At this stage only Odonata species were identified using Clausnitzer & Dijkstra (in press). On collection three characteristics were recorded: species affiliation, sex, and state of maturity. The specimens were preserved in low grade etha-

nol which made the final identification difficult. Two specimens were particularly difficult to identify. One was badly damaged, making identification impossible and the second was identified with supposition because the species affiliation could not be confirmed. The state of maturity of specimens posed the greatest challenge because it was unclear if the lack of body colour pattern was due to age or to the method

Table 1. Locations of all nine light traps set up during the experiment.

Trap ID	Land use	Elevation (m a.s.l.)	Latitude	Longitude
F1	forested	1,531	7° 5.808’	11° 3.518’
F2	forested	1,508	7° 5.829’	11° 3.352’
F3	forested	1,525	7° 5.491’	11° 3.331’
M1	maize field	1,592	7° 5.284’	11° 4.536’
M3	maize field	1,591	7° 5.269’	11° 4.595’
M3	maize field	1,595	7° 5.272’	11° 4.637’
Te1	tea plantation	1,609	7° 5.614’	11° 5.568’
Te2	tea plantation	1,606	7° 5.560’	11° 5.560’
Te3	tea plantation	1,617	7° 5.058’	11° 5.181’

Figure 2. The design of the light traps (picture also shows the primary investigator).

of preservation. Immature specimens were generally identified by the body colour and intensity of the pruinescence on the abdomen, in combination with the hardness of the wing membrane. No detailed discussion was made on these results

as some of them were based on the "best guesses" from the identification. The state of maturity was included in the current paper for general orientation only and should not be interpreted in future studies.

A review of all known records of odonates coming to artificial light sources was prepared by reviewing the published literature and consulting other experts, acknowledged here. The discussion was performed on the information about Odonata imago only. Responses of larvae to the light sources must be investigated separately as the results from the experiments are inconsistent in their findings.

Results

A total of 94 specimens belonging to six odonate species were collected with four of the light traps from Nigeria. Table 2 represents the total catch per trap and date.

All six species were included in another table containing a total of 415 records of Odonata coming to light. These records are from the literature or provided by experts (Table 3, see appendix). The species from Nigeria are recorded for the first time from light traps, which increases the overall number of odonate taxa recorded from light sources to 198 (Table 4, see appendix). As the list includes a large number of records from various parts of the world, a unified approach was preferred while assessing the current taxonomic species status. With one exception, species were included according to the World List of Odonata (Schorr & Paulson 2011). Thus some original published records may not match the entries or may not agree completely with the taxonomy currently suggested by other authors. *Orthetrum camerunense* Gambles, 1959 is the only species whose taxonomy differs from Schorr & Paulson (2011), where it is given as synonym of *Orthetrum caffrum* (Burmeister, 1839). Here a full separate species rank is preferred following the unpublished key of Clausnitzer & Dijkstra (in press) which specifically deals with African Odonata.

Discussion

Odonates are considered predominantly diurnal insects with few species active during morning and evening twilight (eocrepuscular), and few others flying in evening twilight (crepuscular) (Corbet 1999). Adults are sometime visitors of moth traps and have also been found actively flying near lanterns (Feulner 2007), candles (Pemberton 1995, Wesenberg-Lund 1913), lighted buildings or vessels (Askew et al. 1998, Averill 1995, Campos 1931, Dannreuther 1935, Mitra 1974, Morley 1919, Morton 1932, Paine 1996b, Platt & Harrison 1994, Schneider 1992, Tani 1998, Walker & Pittaway 1987, Yamane & Hashiguchi 1994, Young 1967), street lights (Askew et al. 1998), searchlights (Bartenef 1933), flashlights (Honda 2003). This type of behaviour is generally reported as "surprising" (Morley 1919), "uncharacteristic" (Yosef 1994) or "curious" (Young 1967). The prevalent opinion is that these species have been *at-*

Table 2. Odonata species collected during the light trap experiment in Nigeria.

Species	M2				Te1				Te2				Te3				
	male		female		male		female		male		female		male		female		
	immature	mature	immature	mature	immature	mature	immature	mature	immature	mature	immature	mature	immature	mature	immature	mature	
Crocothemis erythraea (Brullé, 1832)	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-	
Crocothemis sanguinolenta (Burmeister, 1839)	1		1		-	-	1	-	-	-	-	-	-	-	-	-	
Orthetrum camerunense Gambles, 1959	3	15	4	2	22	28	-	-	2	4	1	-	3	1	-	1	
Orthetrum chrysostigma (Burmeister, 1839)	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	
Orthetrum ? guineense Ris, 1909	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	
Palpopleura portia (Drury, 1773)	-	-	-	-		1	-	-	-	-	-	-	-	-	-	-	
Total number	4	15	5	2	25	30	1	0	2	4	1	0	3	1	0	1	
Total per site	26				56*				7				5				

tracted to light, which infers a preference for specific wave lengths of the light. Indeed, comparing the efficacy of different light sources, Ramamurthy et al. (2010) established that mercury lamps were better than UV and black light sources, providing more than 70% of the total Odonata catch. Other research has provided stronger indications of some species being lured to light. Borisov (1990) used the term phoxene (introduced by Gornostaev 1984) to denote animals that move towards artificial light. He distinguished 8 odonate species obligatory photoxenes and 12 facultative photoxens from SW Tajikistan. However, the total sample sizes were strongly influenced by the type of light source. Theischinger (2003, 2010) suggested that *Austrocnemis macculochi* (Tillyard, 1926) and *Austrocordulia refracta* Tillyard, 1909 respectively have an attraction to artificial light. Those two species have been collected regularly and in large numbers near artificial light sources. Sharma et al. (2000) set up an Odonata light trap experiment and reported 14 species with *Diplacodes trivialis* (Rambur, 1842), *Brachythemis contaminata* (Fabricius, 1793) and *Agriocnemis pygmaea* (Rambur, 1842) being the most numerous and therefore appear to be light-attracted. Parr (2006b) refers to an observation when *Aeshna grandis* (Linnaeus, 1758) was lured in the light trap just few minutes after its initial operation. Frost (1971) summarised 12 years of sampling records carried out with light traps at the Archbold Biological Station, Florida. He used data on *Pachydiplax longipennis* (Burmeister, 1839) to support the view that some Odonata are attracted to light, with 96 specimens having been col-

lected in one month. The majority of the specimens were sampled during calm nights, thus not disturbed by humans or bad weather conditions.

However, a number of theories have been proposed to explain odonate captures by light traps. Borisov (2007) outlines three groups of obligatory photoxenes:

- Individuals, which during warm periods of the year could embark on activities during the night such as searching for food, flying to roosting places and copulation.
- Species whose adults emerge during the night.
- Entirely diurnal species active in high temperature, low humidity and direct sun light. However, some predominantly teneral individuals arrive to the light sources.

In summary, Borisov (2007) suggested that obligatory photoxenes appear to be individuals behaving differently from their typical behaviour when they experience extremes in weather conditions or unusual situations. A summary of the theories explaining this natural phenomenon is provided below.

Night emergence of imago

Borisov (2004) considered night emergence as a means for regulating mating, avoiding predators and desiccation. Adults emerging during the night have no experience and could easily be confused by the bright rays of the light source. Corbet (1981) also considered this phenomenon as important because tenerals performing their maiden flight have been regularly sampled during the experiments done in Trinidad. Showers & Horsnail (2001) reported on an exceptional situation where 187 Zygoptera exuviae were collected from a light trap over 13 days, with a maximum of 56 individuals collected during one night. *Lindenia tetraphylla* (Vander Linden, 1825) was initially identified as a facultative photoxene (Borisov 1990), but transferred to the group of obligatory photoxene due to its night emergence (Borisov 2007). However, not all species whose imago emerge during the night seem to be affected by the light. *Sympecma* species typically emerge at night, but are not included amongst the obligatory phoxene (Borisov 2007).

Escaping from a refuge

Night emergence was used by Mazochin-Porchnakov (1960) to develop a theory explaining light catches. He suggested that the insects travel to light as they come out of their night refuge because they could see a way for a free flight. The light indicates to the animal an open area to fly to. Therefore it is not the light itself which attracts the insects, but the opportunity they perceive as a path towards an open area. In nature open spaces usually better lit and brighter than close-canopied areas. Insects constantly use bright illumination as an indication of a space (emergence from a hollow, or from dense vegetation). Borisov (2007) supported this view with exam-

ples from his odonatological studies. He emphasises that the flight towards a light source could be explained as a movement towards a clear area with UV-light. Campos (1931) concluded that odonates have been captured in the traps while they have been searching for sheltered places. The electrical light was found to be of no importance for them and does not attract these insects.

Prey availability

Borisov (1990) emphasised that odonates may have not been attracted to light, but to the prey which they may find near the light. Some *Anax parthenope* (Selys, 1839) adults, for example, tended to withdraw from the light after being confused and lost orientation close to the source. Corbet (1999) concluded that it was unclear what drives an adult to fly towards the light – the stimulus of the light itself or the potential prey assemblages. He included this type of behaviour in a special Strategy A.1.2 that is believed to increase the foraging efficiency. The same views are shared by other researchers (Sluvko 2007, Richards & Rowe 1994, Wright 1944, Yosef 1994, Young 1967).

Odonates disturbed near light sources

Corbet (1999) suggested that some individuals caught in light traps may have been disturbed by the trap operator and inadvertently flown in. Wright (1944) reported that individuals disturbed by workmen were perching on or near the lights of the cars and feeding on smaller insects. Furthermore, Dumont (2004) suggested that some species may end up in light traps after having been disturbed while roosting at night, and may not normally be night-active at all. Both Dunkle (1978) and Parr (2006b) came to the conclusion that many of the catches by light traps may simply reflect individuals accidentally disturbed near the trap. However, only species which in late evening retain their motion at a certain level, referred to as a *period of potential activity* (Borisov 1990), could be forced to move within the study area. Species in a state of complete inactivity could not be chased off the ground and usually fell to the ground off the perching substrates. Similarly, Bick (1949) collected *Libellula needhami* Westfall, 1943, *A. junius* and *P. longipennis* from their roosting grounds with a simple flashlight.

Further important discussion points

The summary of the above presented theories was prepared following the new records from Nigeria, which initiated a large literature review. It could possibly be expanded in the near future with more data from other publications. Light trapping is a very popular method in entomology. It has provided similar estimates for the relative abundance of grasshoppers compared to sweeping technique (Evans et al. 1983), proved to be effective in studying migration patterns of Heteroptera (Benedek & Jászai 1973), not to mention the key role that light–trapping plays in the study of

moths (Hausmann 2001). Odonata are often part of the by-catch and as such they may be reported at order level only. Nevertheless they do present in the samples collected using light traps. That is why a detailed review of any record of dragonflies coming to light source must consider every other insect group that has been studied by this method. Such a review is an overwhelming task and is out of focus of the present review. However, entomologists are encouraged to add their records (Parr 2006a) in order to achieve a thorough and comprehensive list of Odonata species collected near the light sources. Every piece of new data could open novel discussions to the one presented below.

The literature review considers six other discussion points, either underestimated or neglected so far, as important in explaining odonates' behaviour in relation to artificial light: a) link between Odonata collected by the light traps to the extreme weather conditions and migration, b) low proportion of species and individual odonates compare to other insect groups, c) low representation in the samples of crepuscular species, d) female dominated sex ratio, e) Zygoptera are much underrepresented in the light trap samples than Anisoptera, and f) atypical behaviour near light sources.

Extreme weather conditions and odonates migration

Odonates have often been sampled near light sources when forced to move long distances due to severe change in atmospheric conditions or during their regular annual migration. Al-Houty (1985, 1989) reported on significant numbers of *Selysiothemis nigra* (Vander Linden, 1825) associated with sandstorms. The individuals were obviously exhausted and easy to catch by hand, which is atypical for this species. *S. nigra* is usually difficult to observe and individuals are hard to catch with a net (M. Marinov, per. observ.). Corbet (1981) stated that the number of individuals collected by the light traps was high soon after the onset of the rains, while Ramamurthy et al. (2010) showed a significant positive correlation with average rainfall and Odonata catches by the light traps. Furthermore, *Anax guttatus* (Burmeister, 1839), *Anax ephippiger* (Burmeister, 1839) and *Gynacantha hyalina* Selys, 1882 have been collected during monsoons (Asaithambi & Manickavasagam 2002). *A. ephippiger* is also a well known migrant and is the fourth most often collected species from light sources (Table 4). Averill (1995) reported on a large number of *A. ephippiger* hovering around the decks of a lighted ship when the moon was obscured but they did not occur on cloudless nights. Other species commonly caught in light traps are known for their long distance dispersal which happens in assemblages of tens of thousands individuals. Barrois (1896) reported a single observation of about 60,000 individuals sitting on the electric wires running along roadsides for about 12 km. These were probably *Sympetrum striolatum* (Charpentier, 1840) and *Sympetrum sanguineum* (Müller, 1764), which rank as the first and fifth most often collected species respectively (Table 4). Furthermore, *Aeshna mixta* Latreille, 1805, which ranks second, is a regular migrant bearing the colloquial named *Migrant Hawker*. Riddiford (1992)

refered to a huge number of *A. mixta* described by local people as *clouds of dragonflies* on the night preceding light-trapping. Parr (1996) commented on the high number of reports of migration events involving hundreds of *A. mixta* individuals. Parr (2006b) also attributed all UK records of *S. sanguineum*, *S. striolatum* and *A. mixta* from light traps to the migration mode of those species. *Pantala flavescens* (Fabricius, 1798), third place in Table 4, is perhaps the best example. Its aerial distapersal has been witnessed many times with some extraordinary figures. Feng et al. (2006) reported on the most striking catch ever – 42,161 specimens collected with a search-light trap for one night. They related this massive movement to the nights characterised by fog or slight wind.

Odonates underrepresented in light traps

Despite the high figures presented above odonates usually represent a very low (if anything at all) proportion of the total number of insects caught per light trap. During his 30-years life-time of experience with Noctuidae, the lepidopterologist Stoyan Beshkov has barely found any Odonata in his moth trap. He has been working very intensively in one of the Europe's biodiversity hot spots, (the Rhodopes Mountain in Bulgaria and Greece) with total of 61 Odonata species known so far and at least 3 more expected (Marinov 2004, 2007). Farrow (1984) operated a light trap for 351 nights and collected total of 105,480 specimens with only 19 of them being odonates. A 12-years period of light-trapping on the Florida Peninsula produced as many as 200 specimens from 17 species (Frost 1971). These are a small fraction of the 143 species reported by Frost (1970) for the entire Florida Peninsula. While the total catch of 200 specimens sounds high, it was obtained over a 12-years period. During the same period *Caenis diminuta* Walker, 1853 was represented in the samples with 44,079 specimens collected over only one month (Frost 1963). Moreover, in some years no odonates were collected at all (Frost 1962). It is true that in this occasion the observation was done during the winter months, but Odonata are active on the Peninsula all year around (Chelmick 2005). McGregor et al. (1987) collected total of 1,126,946 insects from the North Island hill country, New Zealand with only 12 individual odonates. New Zealand is generally poor in Odonata species and this is the only record for the country of any imago coming to light.

Low representation of crepuscular and eocrepuscular species

Surprisingly the data indicate that species caught in light traps are mainly known to have well expressed diurnal activities. However crepuscular (feeding) behaviour is known of many species from all continents: Reeves (2003) listed 23 crepuscular species for Australia; Belevich & Yurchenko (2010) presented observations form Eurasia for eight crepuscular Aeshnidae; Williams (1937) discussed the situation for the Americas; Samraoui (1999) provided details for Africa, and Asian crepuscular species were treated in Arai (1985), Orr (2011), Wilson (2001). In contrast eocrepuscular

species, like *T. tillarga* and Gynacanthini, have been recorded less often light sources (Table 4). Corbet (1961) found it interesting that a crepuscular species like *Gynacantha villosa* Grünberg, 1902 was not collected in light traps which caught four other Odonate species. Münchberg (1966) interpreted the ocelli at the vertex region of caput ("frontal eyes") as "receptors for light of low intensity". "Their arrangement in space and dimension indicates that they inform also of the direction of the incident light rays." Probably those ocelli play an important role both in crepuscular activity and attraction by artificial light sources. Adults do need light for orientation and in twilight they probably use their ocelli in a similar manner as Wellington (1974) described for bumblebees. In those insects polarised light and ocelli can prolong foraging, but homing was a problem for bumblebees when they depend on landmarks and have insufficient light for orienteering. That is perhaps why crepuscular and eocrepuscular odonates were very rarely collected with light traps. Those species are probably able to distinguish between the dim light (their natural environment) and atypical light source (artificial light).

Female odonates dominate in light traps

Females outnumbering males around the light sources is another interesting discovery that has been documented by other authors. Dumont (2004) attributed this fact to the cryptic behaviour of the female. High male density near the water edge is commonly observed in odonates, while females visit water significantly less frequently (Corbet 1999). In the present review, females only samples were reported in 57 occasions, while males only were found in 52 samples; females' prevalence in the light traps was observed in 17 instances and males were found to be dominant in nine of the traps. Eleven catches produced equal number for males and females. This perhaps reflects the location in which the light traps have usually been set up, that is in forest clearings away from the water edge. Borisov (1990) established that female *Ischnura evansi* Morton, 1919 were twice as likely to be trapped as males. Similarily females of *Ischnura fountainei* Morton, 1905 were four times as likely to be caught as males when the trap was not operating close to any wetland.

A significant dominance of Anisoptera over Zygoptera

Tunmore (2005) observed that damselflies do not often appear at the light sources. Figure 3 presents a summary of the ratio between Zygoptera and Anisoptera representatives trapped by the artificial light. The dominance of Anisoptera families (83%) may be explained with the observed tendency of trapping mainly migratory species that embark on long distance dispersals. However, Parr (2006b) sought the explanation of this fact in other than biological underlying mechanism because the migration alone does not explain the much lower records of Zygoptera (17%) coming to light compare to Anisoptera. As mentioned above Parr (2006b) did not consider the attraction to light as typical behaviour for this insect order but rather suggested that

most of the captures are due to accidental individuals chased from their temporal refuges.

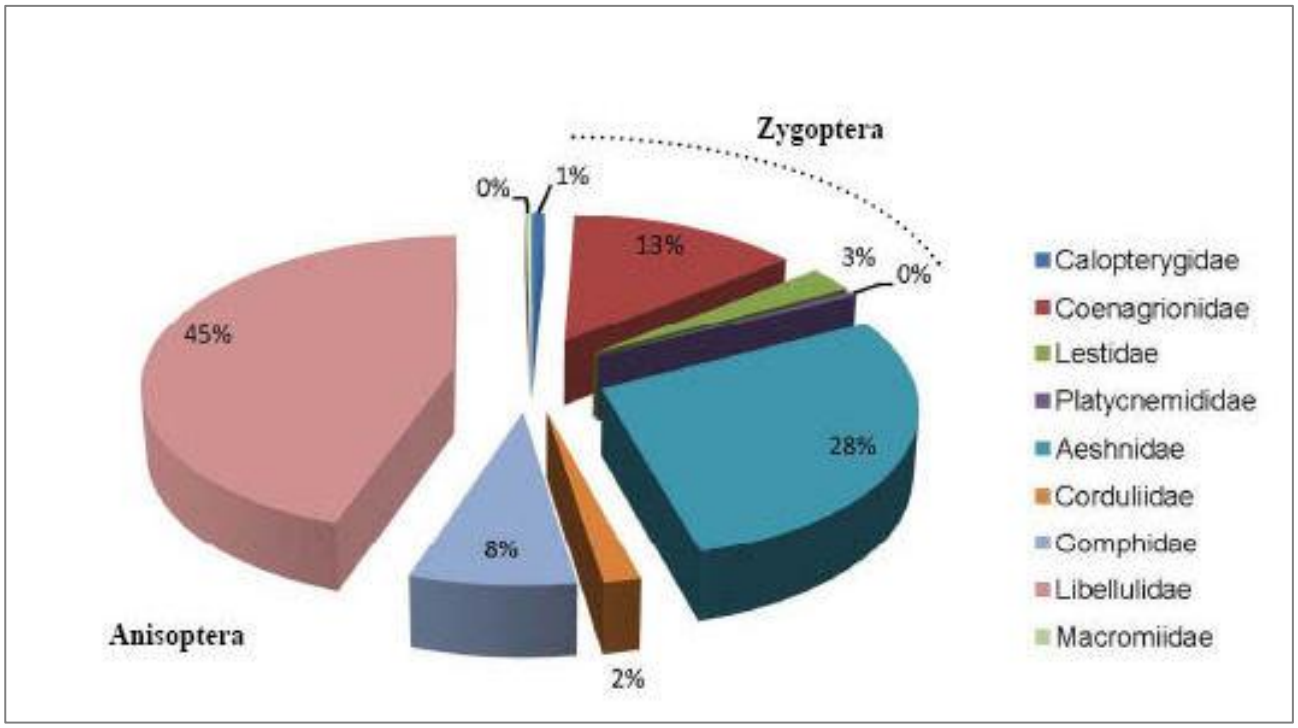

Figure 3. Zygoptera versus Anisoptera families recorded from light traps.

Atypical behaviour near light sources

Atypical behaviour near a light source was reported for the first time by Bayford (1911). On this occasion powerful fliers such as *A. cyanea* were sitting motionless and easily picked up by hand. The research suggested that the atypical behaviour near electric lamps could be triggered by the light source which alters the otherwise powerful sight of odonates. The light may act in the same manner as it does on humans staring directly into a light source. Zieba & Buczynski (2007) have observed *Aeshna viridis* Eversmann, 1836 individuals sitting head on to the lamp so that their body axes were forwardly directed to the source of light. They were easy to collect by hand although the authors do not believe the odonates were completely dazzled (P. Zieba & P. Buczynski per. comm.). Young (1967) has observed *Epitheca princeps* Hagen, 1861 on lighted wall, again easy to pick up by hand and individuals did not fly away when let back on the substrate. An anomalous behavior of curving the abdomen upwards when perched on the wall was observed. This atypical behaviour of *E. princeps* was interesting also for the individuals had repeatedly aggregated at a particular light source although other lamps on the street obviously illuminated the same wave lengths. The dragonfly persistence was attributed to the physical environment of the surroundings, like vegetation. A similar relationship between the vegetation and dragonfly body position at rest was observed by Bartenef (1930). The position and orientation of the adults was determined by the transmitted sun light regardless of the cloudiness and the direct exposure to the sun light of the insects'

bodies. Orientation of the adults on defoliated trees was more constant than those sitting on fully leaved trees. The light transmitted by the leaves obviously has influenced the orientation of the adults in various directions.

Platt & Harrison (1994) provide an anecdotal observation for the atypical behaviour which may have been provoked by the effect which light has on odonates' senses. A male *Anax junius* (Drury, 1773) was observed circling around the lamp bulb for several minutes. The authors believe that the male may have been responding to the prismatic spectral rainbows created by the faceted glass edges of the lamp housing. The green and blue light bands could have created an image of another male. Therefore the flight around the house lamp could be a behavioural response to confront a conspecific rival male. Reflected light could act as a very strong stimulus. Hooper et al. (2006) showed that polarised reflection from a wing surface of *Aeshna cyanea* (Müller, 1764) acted as an intraspecific signalling channel. The responses to this reflection depended on the thickness of the wing membrane and the nature of wax pruinosity. Wiesenborn (2011) concluded that nitrogen concentration in the insect exoskeleton appeared to increase as abundances of resilin and other fluorescent, elastic proteins increased. In *P. longipennis* these structural compounds are responsible for emitting blue fluorescence in the UV light at the area of wing articulation and are probably important nitrogen sources for insectivorous vertebrates. Indeed, Mitra (1974) found that geckoes attack *Crocothemis servilia servilia* (Drury, 1773) and *B. contaminata*, but never *Tholymis tillarga* (Fabricius, 1798) even when individuals coming to light are sitting very close to the lizard. This reaction is linked to the colouration of the *T. tillarga* wings which superficially resemble hymenopterous insects.

A new theory following the Nigerian data

For the purposes of this research it is important to understand how the Nigerian data fit into the discussion. The total sample consists of six species belonging to the same family Libellulidae (Table 2). For light trap Te1 odonates were the only insects collected during the night. All of the species are very common and known as exclusive inhabitants of stagnant water bodies. No crepuscular, eocrepuscular or significant long dispersal activities have been recorded for them. Males totally dominate and as far as the preservation method allows us to tell, the immature individuals were less abundant than mature ones. The general conclusion is that the sample is typical of what one could find during the day along the banks of vegetated pools. However, the light traps were set up at the sample streams and at first sight all new data do not comply entirely with what already has been discussed in the literature. No rain storms or other extreme weather conditions were observed during the time of trapping, no atypical activities were noted around the light traps, odonates totally dominated in some light traps, so did males over females. It is unlikely that the individuals were newly emerged searching for an open space as not any truly teneral

specimens were present in the sample. Those identified as immature possess much harder wing membrane from what are typically observed for tenerals. It is undoubtedly a situation never encountered before which deserves a special attention in future studies. This finding could be explained with the proximity of an irrigation pool occurred within 50m from the light trap Te1. It is possible that the effect of the light in combination with the reflection from the water surface of the tray, which was reported above as an extremely powerful signal for odonates, had created an image of a possible new habitat and lured the males for establishing new territories. It is not difficult to imagine that the warm climate of tropical Nigeria could keep the individuals in the discussed above situation of *period of potential activity*. Perhaps the territorial and predation mode of odonates do not drop so significantly during the night and they could react to such a strong aerial ecological photopollutant (after Horváth et al 2009) like bright artificial light sources.

Conclusions and recommendations

All main discussion points presented above are supportive for the view that odonates are probably not *attracted*, but *confused* by the light. Those insects are a by-product of the total catch per light trap rather than obligatory visitors to light sources. Even when very large catches were made by light traps it does not necessarily mean that they have been attracted to the wave length of the source. It seems more likely that they are caught in light traps due to some combination of other factors. Yamane & Hashiguchi (1994) report on a large number of *P. flavescens* that in a fine windless weather dived into the sea. Some of them were picked up and when released went to the sea again. In no circumstances could such behaviour be attributable to any kind of attraction to death.

However, more studies are needed to establish the true nature of the phenomenon discussed here. Generally light traps are not popular in Odonata studies. Borisov (1990) and Sharma et al. (2000) are so far the only examples of light trap studies specifically designed for capturing adult Odonata. People are encouraged to use this method in odonatological studies as well (Wada & Inoue 1997, Zieba & Buczynski 2007), because light-trapping was found important in studying the phenology and ecology of the adult Anisoptera (Corbet 1981). The study case from Nigeria is supportive of this general conclusion. If indeed the adult odonates in the tropical regions sustain their activity during the night, then the light trapping within those areas is something that must be considered in the odonatological studies. Moreover there are already some very important results that have been obtained during occasional samples using light-trapping method. Holotypes of *Melanocacus mungo* (Needham, 1940), *Hemicordulia gracillima* Fraser, 1944, *Orthetrum icteromelas cinctifrons* Pinhey, 1970, *Gynacantha rammohani* Mitra & Lahiri, 1975, are known from this type of study.

Future studies in this field must consider two additional points not discussed in details by previous research: a) Odonata population dynamics and ratio, and b) individual species perception of light.

The bulk of the data from light-trap investigations was collected from research done on migratory species and with just few exceptions, Odonata species and individuals were far underrepresented in the total catch of insect specimens. This fact could well be a reflection of the total ratio of adult odonates towards other insect orders in nature. This could be supported only with evidences from population studies involving large scale insect sampling encompassing species from various orders within the same investigated area. Such information, is not however available at the moment, but would make a very interesting study for future analyses.

The insect perception of wave length would be another important part of a study towards clarifying whether odonates are indeed confused by light rather than attracted by it. It is well established that the insect vision varies between the species even within the same order or family. Yang & Osorio (1996) have found substantial differences between the laminas in the eyes of *Hemicordulia* and *Sympetrum*, which may perhaps explain the different responses to light of the representatives of the Corduliidae and Libellulidae. Similar comparisons need to be made between crepuscular/eocrepuscular species versus those with well expressed diurnal flying modes. Such research is believed to shed some more light on the dilemma discussed here. It will determine whether the so called *attraction to light sources* of odonates has its origin in the morphology of the eyes, is a physiological reaction or purely an accidental event as inferred here for the majority of species reported so far.

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Appendix

Table 3. A summary of Odonata records (published and new data) from light traps.

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
Japan	Calopterygidae	*Atrocalopteryx atrata* (Selys, 1853)	1 ♂			Tani (1998)
French Guyana	Calopterygidae	*Hetaerina moribunda* Hagen in Selys, 1853	1 ♂			Geijskes (1971)
India	Calopterygidae	*Vestalaria smaragdina* (Selys, 1879)		2		Shull & Nadkerny (1967)
Botswana	Coenagrionidae	*Agriocnemis exilis* Selys, 1872				Pinhey (1976)
India	Coenagrionidae	*Agriocnemis pygmaea* (Rambur, 1842)				Sharma et al. (2000)
Ivory Coast	Coenagrionidae	*Agriocnemis zerafica* Le Roi, 1915	2 ♀♀			Dumont (2004)
USA	Coenagrionidae	*Anomalagrion hastatum* (Say, 1839)				Frost (1964)
USA	Coenagrionidae	*Argia fumipennis* (Burmeister, 1839)				Frost (1975)
Australia	Coenagrionidae	*Austrocnemis macculochi* (Tillyard, 1926)	55 ♂♂, 22 ♀♀			Theischinger (2003)
China	Coenagrionidae	*Cecrion sexlineatum* (Selys, 1883)				Easton & Liang (2000)
China	Coenagrionidae	*Cecrion sexlineatum* (Selys, 1883)			new for the country	Wilson (1996)
India	Coenagrionidae	*Ceriagrion coromandelianum* (Fabricius, 1798)			occasionally at the light source	Andrew & Tembhare (1997)
India	Coenagrionidae	*Ceriagrion coromandelianum* (Fabricius, 1798)				Sharma et al. (2000)

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
Namibia	Coenagrion-idae	*Ceriagrion suave* Ris, 1921	4 ♂♂			Martens et al. (2003)
Russia	Coenagrion-idae	*Coenagrion lanceo-latum* (Selys, 1872)				Kosterin & Dubatolov (2005)
USA	Coenagrion-idae	*Enallagma cardenium* Selys, 1876				Frost (1975)
USA	Coenagrion-idae	*Enallagma civile* (Hagen, 1861)	1 ♂			Wright (1944)
USA	Coenagrion-idae	*Enallagma concisum* Williamson, 1922				Frost (1964)
Russia	Coenagrion-idae	*Enallagma cyathige-rum* (Charpentier, 1840)				Sluvko (2007)
UK	Coenagrion-idae	*Enallagma cyathige-rum* (Charpentier, 1840)				Odin (2006)
UK	Coenagrion-idae	*Enallagma cyathige-rum* (Charpentier, 1840)				Paine (1992b)
UK	Coenagrion-idae	*Enallagma cyathige-rum* (Charpentier, 1840)				Parr (2006b)
UK	Coenagrion-idae	*Enallagma cyathige-rum* (Charpentier, 1840)		1		Parr (2007)
UK	Coenagrion-idae	*Enallagma cyathige-rum* (Charpentier, 1840)			exuviae	Showers & Horsnail (2001)
UK	Coenagrion-idae	*Enallagma cyathige-rum* (Charpentier, 1840)		5		Tunmore (2005)
USA	Coenagrion-idae	*Enallagma laurenti* Calvert, 1919				Frost (1969)
Russia	Coenagrion-idae	*Erythromma najas* (Hansemann, 1823)				Borisov (2007)
UK	Coenagrion-idae	*Erythromma najas* (Hansemann, 1823)			exuviae	Showers & Horsnail (2001)
Russia	Coenagrion-idae	*Erythromma viridulum* Charpentier, 1840				Borisov (1990)
UK	Coenagrion-idae	*Erythromma viridulum* Charpentier, 1840				Jones (2004)
UK	Coenagrion-idae	*Erythromma viridulum* Charpentier, 1840				Parr (2006b)
Brazil	Coenagrion-idae	*Homeoura ? nepos* (Selys, 1876)	3 ♂♂, 1 ♀			Longfield (1929)
Japan	Coenagrion-idae	*Ischnura asiatica* (Brauer, 1865)	1 ♂, 1 ♀		Coll. 27. 07. 2002 at the Omurasaki Center, Ho-kuto City	N. Ishizawa (per. comm.)

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
Bulgaria	Coenagrionidae	*Ischnura elegans* (Vander Linden, 1820)	1 ♂			S. Beshkov (per. observ.)
Poland	Coenagrionidae	*Ischnura elegans* (Vander Linden, 1820)	1 ♂			Buczyński & Buczyńska (2010)
Russia	Coenagrionidae	*Ischnura elegans* (Vander Linden, 1820)		11	Maximum catch for one night	Borisov (1990)
Tadzhikistan	Coenagrionidae	*Ischnura elegans* (Vander Linden, 1820)		1		Borisov (2007)
UK	Coenagrionidae	*Ischnura elegans* (Vander Linden, 1820)				Parr (2006b)
UK	Coenagrionidae	*Ischnura elegans* (Vander Linden, 1820)		2		Tunmore (2005)
Arab Peninsula	Coenagrionidae	*Ischnura evansi* Morton, 1919			thousands of immature individuals at light source far from the nearest known larval habitat (T. Pittaway per. comm.)	Corbet (1999)
Arab Peninsula	Coenagrionidae	*Ischnura evansi* Morton, 1919			to lighted windows	Walker & Pittaway (1987)
Oman	Coenagrionidae	*Ischnura evansi* Morton, 1919			large number attracted to light	Waterson & Pittaway (1991)
Russia	Coenagrionidae	*Ischnura evansi* Morton, 1919		146	maximum catch for one night	Borisov (1990)
Russia	Coenagrionidae	*Ischnura fountainei* Morton, 1905		411	maximum catch for one night	Borisov (1990)
USA	Coenagrionidae	*Ischnura posita* (Hagen, 1861)				Frost (1966)
USA	Coenagrionidae	*Ischnura posita* (Hagen, 1861)				Frost (1969)
Russia	Coenagrionidae	*Ischnura pumilio* (Charpentier, 1825)	1 ♀			Borisov (1990)
Mexico	Coenagrionidae	*Ischnura ramburii* (Selys in Sagra, 1857)			collected at 32, 74 and 106 km distance off the shore	Sparks et al. (1986)
USA	Coenagrionidae	*Ischnura ramburii* (Selys in Sagra, 1857)				Frost (1964)
USA	Coenagrionidae	*Ischnura ramburii* (Selys in Sagra, 1857)	1 ♀			Wright (1944)
India	Coenagrionidae	*Ischnura senegalensis* (Rambur, 1842)			occasionally at the light source	Andrew & Tembhare (1997)

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
India	Coenagrion-idae	*Ischnura senegalensis* (Rambur, 1842)				Sharma et al. (2000)
USA	Coenagrion-idae	*Nehalennia integri-collis* Calvert, 1913				Frost (1964)
USA	Coenagrion-idae	*Nehalennia pallidula* Calvert, 1913				Frost (1969)
Russia	Coenagrion-idae	*Nehalennia speciosa* (Charpentier, 1840)				Kosterin & Dubatolov (2005)
India	Coenagrion-idae	*Pseudagrion decorum* (Rambur, 1842)				Sharma et al. (2000)
India	Coenagrion-idae	*Rhodischnura nursei* (Morton, 1907)			occasionally at the light source	Andrew & Tembhare (1997)
Mexico	Coenagrion-idae	Coenagrionidae indet.		9 ind. from 1 spe-cies	collected at 32, 74 and 106 km dis-tance off the shore	Wolf et al. (1986)
USA	Lestidae	*Archilestes grandis* (Rambur, 1942)				Platt & Harrison (1994)
Japan	Lestidae	*Indolestes peregrinus* (Ris, 1916)	1 ♂		collected on 28. 07.2007 at the Omurasaki Center, Ho-kuto City	N. Ishizawa (per. comm.)
Japan	Lestidae	*Indolestes peregrinus* (Ris, 1916)	1 ♂		collected on 22. 07.2000 at the Omu-rasaki Cen-ter, Hokuto City	N. Ishizawa (per. comm.)
UK	Lestidae	*Lestes sponsa* (Hansemann, 1823)				Paine (1992a)
UK	Lestidae	*Lestes sponsa* (Hansemann, 1823)				Parr (2006b)
USA	Lestidae	*Lestes vidua* Hagen, 1861				Frost (1975)
USA	Lestidae	*Lestes* sp.				Platt & Harrison (1994)
Russia	Lestidae	*Sympecma gobica* Förster, 1900				Borisov (1990)
Russia	Lestidae	*Sympecma paedisca* (Brauer, 1877)		1		Borisov (1990)
Russia	Lestidae	*Sympecma paedisca* (Brauer, 1877)				Kosterin & Dubatolov (2005)
Russia	Lestidae	*Sympecma paedisca* (Brauer, 1877)	1 ♂, 1 ♀			Malikova et al. (2007)
Poland	Platycne-mididae	*Platycnemis pennipes* (Pallas, 1771)	2 ♂♂			Buczyński & Buczyńska (2010)
Switzer-	Platycne-	*Platycnemis pennipes*	2 ♂♂, 2 ♀♀			Hoess & Rezbanyai-

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
land	mididae	(Pallas, 1771)				Reser (2005)
Switzer-land	Aeshnidae	*Aeshna cyanea* (Müller, 1764)	20 ♂♂			Hoess & Rezbanyai-Reser (2005)
Switzer-land	Aeshnidae	*Aeshna cyanea* (Müller, 1764)	1 ♂			Schiess (1982)
UK	Aeshnidae	*Aeshna cyanea* (Müller, 1764)				Bayford (1911)
UK	Aeshnidae	*Aeshna cyanea* (Müller, 1764)	1 ♀		possibly mi-grating indi-vidual	Bland (1997)
UK	Aeshnidae	*Aeshna cyanea* (Müller, 1764)				Moorley (1919)
UK	Aeshnidae	*Aeshna cyanea* (Müller, 1764)				Parr (2006b)
UK	Aeshnidae	*Aeshna cyanea* (Müller, 1764)	1 ♀			Roddis (2007)
Denmark	Aeshnidae	*Aeshna grandis* (Linnaeus, 1758)		1	catching flies around the altar candles	Wesenberg-Lund (1913)
UK	Aeshnidae	*Aeshna grandis* (Linnaeus, 1758)		1		Dannreuther (1937a)
UK	Aeshnidae	*Aeshna grandis* (Linnaeus, 1758)				Paine (1996b)
UK	Aeshnidae	*Aeshna grandis* (Linnaeus, 1758)				Parr (2006b)
Bulgaria	Aeshnidae	*Aeshna mixta* Latreille, 1805	1 ♀			S. Beshkov (per. observ.)
Spain	Aeshnidae	*Aeshna mixta* Latreille, 1805		79		Riddiford (1992)
Switzer-land	Aeshnidae	*Aeshna mixta* Latreille, 1805	21 ♂♂			Hoess & Rezbanyai-Reser (2005)
Switzer-land	Aeshnidae	*Aeshna mixta* Latreille, 1805				Schiess (1982)
UK	Aeshnidae	*Aeshna mixta* Latreille, 1805				Brown (2000)
UK	Aeshnidae	*Aeshna mixta* Latreille, 1805			Hundreds in-dividuals fly-ing pass the ship	Dannreuther (1935)
UK	Aeshnidae	*Aeshna mixta* Latreille, 1805				Dannreuther (1937a)
UK	Aeshnidae	*Aeshna mixta* Latreille, 1805				Dannreuther (1937b)
UK	Aeshnidae	*Aeshna mixta* Latreille, 1805				Deans (2005)
UK	Aeshnidae	*Aeshna mixta* Latreille, 1805		1		Dewick (2000)
UK	Aeshnidae	*Aeshna mixta* Latreille, 1805		1		Dewick (2006)

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
UK	Aeshnidae	*Aeshna mixta* Latreille, 1805		1		Hadley (1980)
UK	Aeshnidae	*Aeshna mixta* Latreille, 1805				Jones (2004)
UK	Aeshnidae	*Aeshna mixta* Latreille, 1805				Odin (2006)
UK	Aeshnidae	*Aeshna mixta* Latreille, 1805		1		Parr (2000b)
UK	Aeshnidae	*Aeshna mixta* Latreille, 1805			20+ records	Parr (2006b)
UK	Aeshnidae	*Aeshna mixta* Latreille, 1805		1		Perrin (2011)
UK	Aeshnidae	*Aeshna mixta* Latreille, 1805		1		Tunmore (2006)
UK	Aeshnidae	*Aeshna mixta* Latreille, 1805		1		Tunmore (2010)
Poland	Aeshnidae	*Aeshna viridis* Eversmann, 1836	1 ♂, 4 ♀♀			Zieba & Buczynski (2007)
UK	Aeshnidae	*Aeshna viridis* Eversmann, 1836	1 ♀			Mattila (2001)
Cayman islands	Aeshnidae	*Anax amazili* (Burmeister, 1839)	1 ♀			Askew et al. (1998)
not specified	Aeshnidae	*Anax amazili* (Burmeister, 1839)	2 ♀♀			Campos (1931)
Cyprus	Aeshnidae	*Anax ephippiger* (Burmeister, 1839)			on the decks of a ship	Averill (1995)
Dubai	Aeshnidae	*Anax ephippiger* (Burmeister, 1839)	1 ♀			Chalmers (2010)
Egypt	Aeshnidae	*Anax ephippiger* (Burmeister, 1839)				Silsby (1993)
India	Aeshnidae	*Anax ephippiger* (Burmeister, 1839)			collected during monsoon	Asaithambi & Manickavasagam (2002)
Iran	Aeshnidae	*Anax ephippiger* (Burmeister, 1839)				Sutton (1966)
Monte-negro	Aeshnidae	*Anax ephippiger* (Burmeister, 1839)	1 ♂			Dumont (1977)
Russia	Aeshnidae	*Anax ephippiger* (Burmeister, 1839)				Borisov (1990)
UAE	Aeshnidae	*Anax ephippiger* (Burmeister, 1839)		1	attracted by the light of a lantern	Feulner (2007)
Uganda	Aeshnidae	*Anax ephippiger* (Burmeister, 1839)	20 ♂♂, 46 ♀♀		all but 1 ♂ were near the light trap	Corbet (1984)
UK	Aeshnidae	*Anax ephippiger* (Burmeister, 1839)	1 ♀			Paine (1996b)
UK	Aeshnidae	*Anax ephippiger* (Burmeister, 1839)				Parr (2006b)
India	Aeshnidae	*Anax guttatus*			predominant-	Andrew & Tembhare

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
		(Burmeister, 1839)			ly collected at light source	(1997)
India	Aeshnidae	*Anax guttatus* (Burmeister, 1839)				Arulprakash & Gunathilagaraj (2010)
India	Aeshnidae	*Anax guttatus* (Burmeister, 1839)			collected during monsoon	Asaithambi & Manickavasagam (2002)
India	Aeshnidae	*Anax guttatus* (Burmeister, 1839)		18		Patil et al. (1982)
Laos	Aeshnidae	*Anax guttatus* (Burmeister, 1839)			lighted candle	Pemberton (1995)
Republic of Maldives	Aeshnidae	*Anax guttatus* (Burmeister, 1839)	1 ♂			Mahlendorf & Martens (2004)
Singapore	Aeshnidae	*Anax guttatus* (Burmeister, 1839)	1 ♀			Norma-Rashid et al. (2008)
Tailand	Aeshnidae	*Anax guttatus* (Burmeister, 1839)	1 ♀			Hämäläinen (1988)
India	Aeshnidae	*Anax immaculifrons* Rambur, 1842			predominantly collected at light source	Andrew & Tembhare (1997)
India	Aeshnidae	*Anax immaculifrons* Rambur, 1842				Sharma et al. (2000)
Russia	Aeshnidae	*Anax imperator* Leach, 1815				Sluvko (2007)
Switzerland	Aeshnidae	*Anax imperator* Leach, 1815	1 ♀			Hoess & Rezbanyai-Reser (2005)
UK	Aeshnidae	*Anax imperator* Leach, 1815				Parr (2006b)
UK	Aeshnidae	*Anax imperator* Leach, 1815		1		Parr (2007)
Mexico	Aeshnidae	*Anax junius* (Drury, 1773)		8	collected at 74, 106 & 160 km distance off the shore	Sparks et al. (1986)
USA	Aeshnidae	*Anax junius* (Drury, 1773)				Beckemeyer (2003)
USA	Aeshnidae	*Anax junius* (Drury, 1773)				Frost (1966)
USA	Aeshnidae	*Anax junius* (Drury, 1773)	1 ♂			Platt & Harrison (1994)
USA	Aeshnidae	*Anax junius* (Drury, 1773)				Wright (1944)
Willis Island, Australia	Aeshnidae	*Anax papuensis* (Burmeister, 1839)		11		Farrow (1984)
Dubai	Aeshnidae	*Anax parthenope* (Selys, 1839)	2 ♀♀			Chalmers (2010)
Egypt	Aeshnidae	*Anax parthenope* (Selys, 1839)				Silsby (1993)

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
India	Aeshnidae	*Anax parthenope* (Selys, 1839)			sitting near light sources	Asaithambi & Manickavasagam (2002)
Oman	Aeshnidae	*Anax parthenope* (Selys, 1839)	1 ♂			Waterson & Pittaway (1991)
Russia	Aeshnidae	*Anax parthenope* (Selys, 1839)				Borisov (1990)
UK	Aeshnidae	*Anax parthenope* (Selys, 1839)	1 ♀			Parr (2006b)
China	Aeshnidae	*Anax parthenope julius* Brauer, 1865				Easton & Liang (2000)
China	Aeshnidae	*Anax parthenope julius* Brauer, 1865		59, 342	caught during 2003 field season	Feng et al. (2006)
Gambia	Aeshnidae	*Anax tristis* Hagen, 1867				Silsby (1999)
off Angola	Aeshnidae	*Anax tristis* Hagen, 1867	1 ♂		60 km from mainland	Schnieder (1992)
Tanganyika	Aeshnidae	*Anax tristis* Hagen, 1867				Pinhey (1961)
France	Aeshnidae	*Boyeria irene* (Fonscolombe, 1838)	1 ♂			Morton (1932)
Canada	Aeshnidae	*Boyeria vinosa* (Say, 1840)	1 ♀			Hutchingso (2001)
not specified	Aeshnidae	*Coryphaeschna adnexa* (Hagen, 1861)	1 ♀			Campos (1931)
USA	Aeshnidae	*Coryphaeschna ingens* (Rambur, 1842)				Frost (1964)
French Guyana	Aeshnidae	*Coryphaeschna viriditas* Calvert, 1952	1 ♂, 1 ♀			Geijskes (1971)
Trinidad	Aeshnidae	*Coryphaeschna viriditas* Calvert, 1952	3 ♂♂, 5 ♀♀			Corbet (1981)
USA	Aeshnidae	*Epiaeschna heros* (Fabricius, 1798)		1		Platt & Harrison (1994)
USA	Aeshnidae	*Gomphaeschna antilope* (Hagen, 1874)				Frost (1964)
India	Aeshnidae	*Gynacantha bayadera* Selys, 1891 (= *G. furcata*?)			predominantly collected at light source	Andrew & Tembhare (1997)
Ivory Coast	Aeshnidae	*Gynacantha bullata* Karsch, 1891	4 ♂♂, 1 ♀			Dumont (2004)
Sarawak, Malaysia	Aeshnidae	*Gynacantha ? dohrni* Krüger, 1899				Dow (2005)
India	Aeshnidae	*Gynacantha hyalina* Selys, 1882				Arulprakash & Gunathilagaraj (2010)
India	Aeshnidae	*Gynacantha hyalina* Selys, 1882			collected during monsoon	Asaithambi & Manickavasagam (2002)
Trinidad	Aeshnidae	*Gynacantha mexicana*	1 ♂			Corbet (1981)

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
		Selys, 1868				
Cayman Islands	Aeshnidae	*Gynacantha nervosa* Rambur, 1842	1 ♀			Askew et al. (1998)
Trinidad	Aeshnidae	*Gynacantha nervosa* Rambur, 1842	4 ♂♂, 1 ♀			Corbet (1981)
USA	Aeshnidae	*Gynacantha nervosa* Rambur, 1842				Frost (1964)
USA	Aeshnidae	*Gynacantha nervosa* Rambur, 1842		2		Ihssen (1997)
India	Aeshnidae	*Gynacantha rammo-hani* Mitra & Lahiri, 1975	1 ♀		holotype	Mitra & Lahiri (1975)
Tailand	Aeshnidae	*Gynacantha saltatrix* Martin, 1909				Hämäläinen (1987a)
Borneo, Malaysia	Aeshnidae	*Gynacantha* sp.				Orr (1995)
Ivory Coast	Aeshnidae	*Gynacantha* sp.	1♀			Dumont (2004)
not specified	Aeshnidae	*Gynacantha* sp.		1		Campos (1931)
Sarawak, Malaysia	Aeshnidae	*Gynacantha* sp.	1 ♀			Dow (2005)
Sarawak, Malaysia	Aeshnidae	*Heliaeschna crassa* Krüger, 1899				Dow (2005)
Borneo, Malaysia	Aeshnidae	*Heliaeschna* sp.				Orr (1995)
Sarawak, Malaysia	Aeshnidae	*Heliaeschna* sp.	1 ♀			Dow (2005)
Malay Penin-sula & Indonesia	Aeshnidae	*Indaeschna grubaueri* (Förster, 1904)				Lieftinck (1954)
French Guyana	Aeshnidae	*Neuraeschna clavifor-cipata* Martin, 1909	1 ♂			Geijskes (1971)
French Guyana	Aeshnidae	*Neuraeschna costalis* (Burmeister, 1839)	1 ♀			Geijskes (1971)
Borneo, Malaysia	Aeshnidae	*Oligaeschna* sp.				Orr (1995)
Malay Penin-sula	Aeshnidae	*Periaeschna laidlawi* (Förster, 1908)	immature ♀			Lieftinck (1954)
Sarawak, Malaysia	Aeshnidae	*Tetracanthagyna brun-nea* McLachlan, 1898	1 ♀			Dow (2005)
Malay Penin-sula	Aeshnidae	*Tetracanthagyna plagiata* (Waterhouse, 1877)				Lieftinck (1954)
Cayman Islands	Aeshnidae	*Triacanthagyna septi-ma* (Selys in Sagra, 1857)	1 ♀			Askew et al. (1998)
not	Aeshnidae	*Triacanthagyna septi-*				Campos (1931)

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
specified		*ma* (Selys in Sagra, 1857)				
Trinidad	Aeshnidae	*Triacanthagyna septima* (Selys in Sagra, 1857)	1 ♀			Corbet (1981)
USA	Aeshnidae	*Triacanthagyna trifida* (Rambur, 1842)				Frost (1964)
Mexico	Aeshnidae	Aeshnidae indet.		8 ind. from 1 sp.	collected at 74, 106 & 160 km distance from the shore	Wolf et al. (1986)
Australia	Corduliidae	*Austrocordulia refracta* Tillyard, 1909				Theischinger (2010)
USA	Corduliidae	*Epitheca cynosura* (Say, 1840)				Frost (1966)
USA	Corduliidae	*Epitheca princeps* Hagen, 1861	63 ♂♂, 15 ♀♀		for 17 consequitive nights	Young (1967)
USA	Corduliidae	*Epitheca sepia* (Gloyd, 1933)				Frost (1966)
Malaysia	Corduliidae	*Hemicordulia gracillima* Fraser, 1944	1 ♀		holotype	Fraser (1944)
USA	Corduliidae	*Neurocordulia yamaskanensis* (Provancher, 1875)	1 ♀			Montgomery (1955)
Switzerland	Corduliidae	*Oxygastra curtisii* (Dale, 1834)	1 ♀			Hoess & Rezbanyai-Reser (2005)
Thailand	Gomphidae	*Acrogomphus minor* Laidlaw, 1931	1 ♀		paratype	Laidlaw (1931)
Russia	Gomphidae	*Anormogomphus kiritschenkoi* Bartenev, 1913	1 ♀		teneral female	Borisov (1990)
Australia	Gomphidae	*Austrogomphus australis* Dale in Selys, 1854				Corbet (1999)
Malaysia	Gomphidae	*Burmagomphus arthuri* Lieftinck, 1953	1 ♀		new for the country	Hämäläinen (2000)
French Guyana	Gomphidae	*Cacoides latro* (Erichson, 1848)	2 ♀♀			Geijskes (1971)
Russia	Gomphidae	*Gomphus flavipes lineatus* Bartenev, 1929			tenerals	Borisov (2007)
Peru	Gomphidae	*Heterogomphus* sp.				Burmeister (2006)
Thailand	Gomphidae	*Ictinogomphus decoratus melaenops* Selys, 1857	1 ♀			Hämäläinen (1987b)
India	Gomphidae	*Ictinogomphus rapax* (Rambur, 1842)			Predominantly collected at light source	Andrew & Tembhare (1997)
India	Gomphidae	*Ictinogomphus rapax* (Rambur, 1842)			sitting near light sources	Asaithambi & Manickavasagam (2002)

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
India	Gomphidae	*Ictinogomphus rapax* (Rambur, 1842)				Sharma et al. (2000)
Kuwait	Gomphidae	*Lindenia tetraphylla* (Vander Linden, 1825)			sampled during a sand storm	Al-Houty (1985)
Kuwait	Gomphidae	*Lindenia tetraphylla* (Vander Linden, 1825)			sampled during a sand storm	Al-Houty (1989)
Russia	Gomphidae	*Lindenia tetraphylla* (Vander Linden, 1825)	1 ♂, 1 ♀		teneral female	Borisov (1990)
Russia	Gomphidae	*Lindenia tetraphylla* (Vander Linden, 1825)	1 ♀			Skvortsov & Kutaev (2010)
Indonesia	Gomphidae	*Macrogomphus p. parallelogramma* (Burmeister, 1839)	♀♀			Lieftinck (1954)
USA	Gomphidae	*Melanocacus mungo* (Needham, 1940)	2 ♂♂		teneral + holotype	Needham (1940)
Uganda	Gomphidae	*Notogomphus lujai* (Schouteden, 1934)	1 ♂		mature individual	Corbet (1961)
Russia	Gomphidae	*Onychogomphus flexuosus* (Schneider, 1845)	1 ♂, 1 ♀		teneral female	Borisov (1990)
Bulgaria	Gomphidae	*Onychogomphus forcipatus* (Linnaeus, 1758)	1 ♂			S. Beshkov & M. Beshkova (per. observ.)
Switzerland	Gomphidae	*Onychogomphus f. forcipatus* (Linnaeus, 1758)	1 ♂, 1 ♀			Hoess & Rezbanyai-Reser (2005)
Russia	Gomphidae	*Ophiogomphus reductus* Calvert, 1898	1 ♀			Borisov (1990)
Namibia	Gomphidae	*Paragomphus cognatus* (Rambur, 1842)	1 ♂			Martens et al. (2003)
India	Gomphidae	*Paragomphus lineatus* (Selys, 1850)			predominantly collected at light source	Andrew & Tembhare (1997)
Sudan	Gomphidae	*Paragomphus pumilio* (Rambur, 1842)				Ris (1924)
French Guyana	Gomphidae	*Phyllogomphoides andromeda* (Selys, 1869)	1 ♂, 1 ♀			Geijskes (1971)
French Guyana	Gomphidae	*Phyllogomphoides fuliginosus* (Hagen in Selys, 1854)	1 ♂			Geijskes (1971)
Peru	Gomphidae	*Phyllogomphoides selysi* (Navás, 1924)		2		Dunkle (1989)
Uganda	Gomphidae	*Phyllogomphus selysi* Schouteden, 1933	1 ♀			Dijkstra et al. (2006)
French Guyana	Gomphidae	*Progomphus brachycnemis* Needham, 1944	1 ♀		juvenile	Geijskes (1971)

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
China	Gomphidae	*Sinictinogomphus clavatus* (Fabricius, 1775)				Easton & Liang (2000)
Ivory Coast	Libellulidae	*Aethriamanta rezia* Kirby, 1889	1 ♂			Dumont (2004)
French Guyana	Libellulidae	*Anatya guttata* (Erichson, 1848)	1 ♂			Geijskes (1971)
Trinidad	Libellulidae	*Anatya guttata* (Erichson, 1848)	1 ♀			Corbet (1981)
India	Libellulidae	*Brachydiplax sobrina* (Rambur, 1842)				Sharma et al. (2000)
Trinidad	Libellulidae	*Brachymesia furcata* (Hagen, 1861)	1 ♀			Corbet (1981)
Trinidad	Libellulidae	*Brachymesia herbida* (Gundlach, 1889)	1 ♂			Corbet (1981)
India	Libellulidae	*Brachythemis contaminata* (Fabricius, 1793)			prey of gecko	Mitra (1974)
India	Libellulidae	*Brachythemis contaminata* (Fabricius, 1793)				Sharma et al. (2000)
India	Libellulidae	*Brachythemis contaminata* (Fabricius, 1793)		3		Shull & Nadkerny (1967)
Uganda	Libellulidae	*Brachythemis leucosticta* (Burmeister, 1839)				Corbet (1959)
India	Libellulidae	*Bradinopyga geminata* (Rambur, 1842)			occasionally at the light source	Andrew & Tembhare (1997)
India	Libellulidae	*Bradinopyga geminata* (Rambur, 1842)		1		Shull & Nadkerny (1967)
Malay Peninsula & Indonesia	Libellulidae	*Camacinia gigantea* (Brauer, 1867)				Lieftinck (1954)
USA	Libellulidae	*Celithemis eponina* (Drury, 1773)				Frost (1975)
USA	Libellulidae	*Celithemis ornata* (Rambur, 1842)				Frost (1964)
Ivory Coast	Libellulidae	*Chalcostephia flavifrons* Kirby, 1889	4 ♂♂, 2 ♀♀			Dumont (2004)
Nigeria	Libellulidae	*Crocothemis erythraea* (Brullé, 1832)				this paper
Nigeria	Libellulidae	*Crocothemis sanguinolenta* (Burmeister, 1839)				this paper
India	Libellulidae	*Crocothemis servilia* (Drury, 1773)			occasionally at the light source	Andrew & Tembhare (1997)

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
India	Libellulidae	*Crocothemis servilia* (Drury, 1773)			prey of gecko	Mitra (1974)
India	Libellulidae	*Crocothemis servilia* (Drury, 1773)				Sharma et al. (2000)
Russia	Libellulidae	*Crocothemis servilia* (Drury, 1773)		30	maximum catch for one night	Borisov (1990)
Russia	Libellulidae	*Diplacodes lefebvrii* (Rambur, 1842)				Borisov (1990)
Uganda	Libellulidae	*Diplacodes luminans* (Karsch, 1893)	21 ♂♂, 27 ♀♀			Corbet (1984)
India	Libellulidae	*Diplacodes trivialis* (Rambur, 1842)				Sharma et al. (2000)
USA	Libellulidae	*Erythemis simplicicollis* (Say, 1840)				Frost (1975)
USA	Libellulidae	*Erythemis simplicicollis* (Say, 1840)				Wright (1944)
French Guyana	Libellulidae	*Erythrodiplax famula* (Erichson, 1848)	12 ♂♂, 24 ♀♀			Geijskes (1971)
not specified	Libellulidae	*Erythrodiplax fusca* (Rambur, 1842)	1 ♀			Campos (1931)
Trinidad	Libellulidae	*Erythrodiplax fusca* (Rambur, 1842)	1 ♂			Corbet (1981)
French Guyana	Libellulidae	*Erythrodiplax haematogastra* (Burmeister, 1839)	1 ♂			Geijskes (1971)
French Guyana	Libellulidae	*Erythrodiplax longitudinalis* (Ris, 1919)	6 ♂♂, 3 ♀♀			Geijskes (1971)
USA	Libellulidae	*Erythrodiplax minuscula* (Rambur, 1842)				Frost (1964)
Trinidad	Libellulidae	*Erythrodiplax umbrata* (Linnaeus, 1758)	1 ♂			Corbet (1981)
Ivory Coast	Libellulidae	*Hemistigma albipuncta* (Rambur, 1842)	1 ♀			Dumont (2004)
Ukraine	Libellulidae	*Leucorrhinia pectoralis* (Charpentier, 1825)	1 ♂, 1 ♀			Bartenef (1933)
USA	Libellulidae	*Libellula auripennis* Burmeister, 1839				Wright (1944)
USA	Libellulidae	*Libellula axilena* Westwood, 1837				Yosef (1994)
UK	Libellulidae	*Libellula quadrimaculata* Linnaeus, 1758				Dannreuther (1935)
Thailand	Libellulidae	*Macrodiplax cora* (Kaup in Brauer, 1867)	1 ♂			Hämäläinen (1987b)
French Guyana	Libellulidae	*Micrathyria aequalis* (Hagen, 1861)	1 ♀			Geijskes (1971)
French Guyana	Libellulidae	*Micrathyria atra* (Martin, 1897)	1 ♀			Geijskes (1971)
Trinidad	Libellulidae	*Micrathyria atra* (Martin, 1897)	1 ♀			Corbet (1981)

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
Trinidad	Libellulidae	*Micrathyria laevigata* Calvert, 1909	1 ♀			Corbet (1981)
French Guyana	Libellulidae	*Micrathyria mengeri* Ris, 1919	1 ♀			Geijskes (1971)
Trinidad	Libellulidae	*Micrathyria ocellata* Martin, 1897	1 ♂, 1 ♀			Corbet (1981)
French Guyana	Libellulidae	*Nephepeltia flavifrons* (Karsch, 1889)	1 ♀			Geijskes (1971)
Malaysia	Libellulidae	*Neurothemis tullia tullia* (Drury, 1773)		1		Lieftinck (1954)
Uganda	Libellulidae	*Notiothemis robertsi* Fraser, 1944	1 ♂		mature individual	Corbet (1961)
Ivory Coast	Libellulidae	*Olpogastra lugubris* (Karsch, 1895)	1 ♀			Dumont (2004)
French Guyana	Libellulidae	*Orthemis ferruginea* (Fabricius, 1775)	1 ♀			Geijskes (1971)
Trinidad	Libellulidae	*Orthemis ferruginea* (Fabricius, 1775)	8 ♂♂, 5 ♀♀			Corbet (1981)
Trinidad	Libellulidae	*Orthemis sulphurata* Hagen, 1868	2 ♀♀			Corbet (1981)
Ivory Coast	Libellulidae	*Orthetrum brachiale* (Palisot de Beauvois, 1805)	2 ♂♂, 4 ♀♀			Dumont (2004)
Russia	Libellulidae	*Orthetrum brunneum* (Fonscolombe, 1837)				Borisov (1990)
Nigeria	Libellulidae	*Orthetrum camerunense* Gambles, 1959				this paper
Switzerland	Libellulidae	*Orthetrum cancellatum* (Linnaeus, 1758)	1 ♀			Hoess & Rezbanyai-Reser (2005)
Nigeria	Libellulidae	*Orthetrum chrysostigma* (Burmeister, 1839)				this paper
Nigeria	Libellulidae	*Orthetrum* ? *guineense* Ris, 1909				this paper
Uganda	Libellulidae	*Orthetrum hintzi* Schmidt, 1951	1 ♂		mature individual	Corbet (1961)
not specified	Libellulidae	*Orthetrum icteromelas cinctifrons* Pinhey, 1970	1 ♂		holotype	Dijkstra (2007)
Uganda	Libellulidae	*Orthetrum julia* Kirby, 1900	1 ♂, 2 ♀♀ probably of this species		mature individual	Corbet (1961)
India	Libellulidae	*Orthetrum sabina* (Drury, 1770)			occasionally at the light source	Andrew & Tembhare (1997)
India	Libellulidae	*Orthetrum sabina* (Drury, 1770)				Sharma et al. (2000)
Russia	Libellulidae	*Orthetrum sabina* (Drury, 1770)				Borisov (1990)
Uganda	Libellulidae	*Orthetrum* ? *trinacria* (Selys, 1841)			identified by supposition	Corbet (1959)

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
Japan	Libellulidae	*Orthetrum triangulare melania*(Selys, 1883)	1 ♂, 1 ♀		collected on 27.07. 2002 at the Omurasaki Center, Hokuto City	N. Ishizawa (per. comm.)
India	Libellulidae	*Orthetrum* sp.	3			Shull & Nadkerny (1967)
USA	Libellulidae	*Pachydiplax longipennis* (Burmeister, 1839)				Frost (1964)
USA	Libellulidae	*Pachydiplax longipennis* (Burmeister, 1839)	43 ♂♂, 53 ♀♀		collected for one month	Frost (1971)
USA	Libellulidae	*Pachydiplax longipennis* (Burmeister, 1839)				Frost (1975)
USA	Libellulidae	*Pachydiplax longipennis* (Burmeister, 1839)				Wright (1944)
Nigeria	Libellulidae	*Palpopleura portia* (Drury, 1773)				this paper
China	Libellulidae	*Pantala flavescens* (Fabricius, 1798)		96	caught during 2003 field season	Feng et al. (2006)
French Guyana	Libellulidae	*Pantala flavescens* (Fabricius, 1798)	1 ♂			Geijskes (1971)
India	Libellulidae	*Pantala flavescens* (Fabricius, 1798)				Sharma et al. (2000)
India	Libellulidae	*Pantala flavescens* (Fabricius, 1798)				Shull & Nadkerny (1967)
Japan	Libellulidae	*Pantala flavescens* (Fabricius, 1798)		10		Asahina & Turuoka (1967)
Japan	Libellulidae	*Pantala flavescens* (Fabricius, 1798)				Honda (2003)
Japan	Libellulidae	*Pantala flavescens* (Fabricius, 1798)				Inoue (1998)
Japan	Libellulidae	*Pantala flavescens* (Fabricius, 1798)			tens of kilometres off shore	Yamane & Hashiguchi (1994)
Republic of Maldives	Libellulidae	*Pantala flavescens* (Fabricius, 1798)		1		Mahlendorf & Martens (2004)
Russia	Libellulidae	*Pantala flavescens* (Fabricius, 1798)				Borisov (1990)
Trinidad	Libellulidae	*Pantala flavescens* (Fabricius, 1798)	1 ♂			Corbet (1981)
Willis Island, Australia	Libellulidae	*Pantala flavescens* (Fabricius, 1798)		3		Farrow (1984)
Cayman islands	Libellulidae	*Pantala hymenaea* Say, 1840		1		Askew et al. (1998)

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
Mexico	Libellulidae	*Pantala hymenaea* Say, 1840		1	collected at 160 km off shore	Sparks et al. (1986)
India	Libellulidae	*Pantala* sp.		36		Patil et al. (1982)
Namibia	Libellulidae	*Parazyxomma flavicans* (Martin, 1908)	1 ♀			Martens et al. (2003)
Uganda	Libellulidae	*Parazyxomma flavicans* (Martin, 1908)				Corbet (1959)
Trinidad	Libellulidae	*Perithemis mooma* Kirby, 1889	1 ♂			Corbet (1981)
USA	Libellulidae	*Perithemis tenera* (Say, 1840)				Montgomery (1955)
Singapore	Libellulidae	*Pornothemis serrata* Krüger, 1902	1 ♂			Norma-Rashid et al. (2008)
Kuwait	Libellulidae	*Selysiothemis nigra* (Vander Linden, 1825)		great number	sampled during a sand storm	Al-Houty (1985)
Kuwait	Libellulidae	*Selysiothemis nigra* (Vander Linden, 1825)			sampled during a sand storm	Al-Houty (1989)
Russia	Libellulidae	*Selysiothemis nigra* (Vander Linden, 1825)				Borisov (1990)
Russia	Libellulidae	*Selysiothemis nigra* (Vander Linden, 1825)	1 ♀			Skvortsov & Kutaev (2010)
USA	Libellulidae	*Sympetrum ambiguum* (Rambur, 1842)				Montgomery (1955)
Russia	Libellulidae	*Sympetrum arenicolor* Jödicke, 1994				Borisov (2007)
Russia	Libellulidae	*Sympetrum danae* (Sulzer, 1776)				Kosterin & Dubatolov (2005)
UK	Libellulidae	*Sympetrum danae* (Sulzer, 1776)				Parr (2006b)
Russia	Libellulidae	*Sympetrum depressiusculum* (Selys, 1841)				Kosterin & Dubatolov (2005)
Russia	Libellulidae	*Sympetrum eroticum* (Selys, 1883)	1 ♀			Malikova et al. (2007)
Japan	Libellulidae	*Sympetrum eroticum eroticum* (Selys, 1883)	1 ♂		collected on 22.07.2000 at the Omurasaki Center, Hokuto City	N. Ishizawa (per. comm.)
UK	Libellulidae	*Sympetrum flaveolum* (Linnaeus, 1758)	1 ♂			Mendel & Marsh (1995)
UK	Libellulidae	*Sympetrum flaveolum* (Linnaeus, 1758)				Paine (1995)
UK	Libellulidae	*Sympetrum flaveolum* (Linnaeus, 1758)	1 ♂			Paine (1996a)
UK	Libellulidae	*Sympetrum flaveolum*				Parr (2006b)

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
		(Linnaeus, 1758)				
Russia	Libellulidae	*Sympetrum fonsco-lombii* (Selys, 1840)				Borisov (1990)
UK	Libellulidae	*Sympetrum fonsco-lombii* (Selys, 1840)				Parr (2006b)
UK	Libellulidae	*Sympetrum fonsco-lombii* (Selys, 1840)	1 ♂			Tunmore (2002)
UK	Libellulidae	*Sympetrum fonsco-lombii* (Selys, 1840)			small numbers	Tunmore (2007)
Switzer-land	Libellulidae	*Sympetrum sangui-neum* (Müller, 1764)	1 ♀			Hoess & Rezbanyai-Reser (2005)
UK	Libellulidae	*Sympetrum sangui-neum* (Müller, 1764)	1 ♂			Mendel & Marsh (1995)
UK	Libellulidae	*Sympetrum sangui-neum* (Müller, 1764)				Odin (2006)
UK	Libellulidae	*Sympetrum sangui-neum* (Müller, 1764)	1 ♀			Paine (1992a)
UK	Libellulidae	*Sympetrum sangui-neum* (Müller, 1764)				Paine (1995)
UK	Libellulidae	*Sympetrum sangui-neum* (Müller, 1764)		9		Parr (2000a)
UK	Libellulidae	*Sympetrum sangui-neum* (Müller, 1764)				Parr (2001)
UK	Libellulidae	*Sympetrum sangui-neum* (Müller, 1764)		12		Parr (2005)
UK	Libellulidae	*Sympetrum sangui-neum* (Müller, 1764)			20+ records	Parr (2006b)
UK	Libellulidae	*Sympetrum sangui-neum* (Müller, 1764)			single indivi-duals	Parr (2007)
Spain	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)		4		Riddiford (1992)
Switzer-land	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)	1 ♂, 3 ♀♀			Hoess & Rezbanyai-Reser (2005)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)				Cade (2004)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)				Dannreuther (1937b)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)				Deans (2005)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)		1		Deans (2006a)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)				Deans (2006b)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)				Deans (2008)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)				Deans (2009)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)		1		Deans (2010)

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)		10	for a 20-days period	Dewick (1999)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)		19	total for the season	Dewick (2000)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)				Dewick (2006)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)	1 ♂			Dewick (2011)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)				Moore (2009)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)		42		Odin (2006)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)	1 ♂			Paine (1996a)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)		19		Parr (2000a)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)		1		Parr (2001)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)		26		Parr (2005)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)			approxima-tely 100 re-cords	Parr (2006b)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)			occasionally at the light source	Tunmore (2005)
UK	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)				Tunmore (2010)
Russia	Libellulidae	*Sympetrum vulgatum* (Linnaeus, 1758)				Borisov (2007)
Switzer-land	Libellulidae	*Sympetrum vulgatum* (Linnaeus, 1758)	2 ♂ ♂			Hoess & Rezbanyai-Reser (2005)
Russia	Libellulidae	*Sympetrum vulgatum decoratum* Selys, 1884				Borisov (1990)
Switzer-land	Libellulidae	*Sympetrum* sp.				Aubert (1964)
UK	Libellulidae	*Sympetrum* sp.				Dewick (2001)
UK	Libellulidae	*Sympetrum* sp.		18		Parr (2001)
USA	Libellulidae	*Sympetrum* sp.		3		Platt & Harrison (1994)
Trinidad	Libellulidae	*Tauriphila australis* (Hagen, 1867)	1 ♂			Corbet (1981)
Trinidad	Libellulidae	*Tholymis citrina* Hagen, 1867	1 ♀			Corbet (1981)
India	Libellulidae	*Tholymis tillarga* (Fabricius, 1798)				Arulprakash & Gunathilagaraj (2010)
India	Libellulidae	*Tholymis tillarga* (Fabricius, 1798)			mostly collec-ted sitting	Asaithambi & Manickavasagam

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
					near the light source	(2002)
India	Libellulidae	*Tholymis tillarga* (Fabricius, 1798)				Mitra (1974)
India	Libellulidae	*Tholymis tillarga* (Fabricius, 1798)				Sharma et al. (2000)
Ivory Coast	Libellulidae	*Tholymis tillarga* (Fabricius, 1798)	15 ♂♂, 34 ♀♀			Dumont (2004)
off Angola	Libellulidae	*Tholymis tillarga* (Fabricius, 1798)	2 ♂♂, 1 ♀		60 km from mainland	Schnieder (1992)
Willis Island, Australia	Libellulidae	*Tholymis tillarga* (Fabricius, 1798)		4		Farrow (1984)
not specified	Libellulidae	*Tramea basilaris* (Palisot de Beauvois, 1805)				Campos (1931)
Uganda	Libellulidae	*Tramea basilaris* (Palisot de Beauvois, 1805)	6 ♂♂, 9 ♀♀			Corbet (1984)
India	Libellulidae	*Tramea basilaris burmeisteri* Kirby, 1889			occasionally at the light source	Andrew & Tembhare (1997)
Trinidad	Libellulidae	*Tramea calverti* Muttkowski, 1910	2 ♂♂, 4 ♀♀			Corbet (1981)
USA	Libellulidae	*Tramea carolina* (Linnaeus, 1763)				Frost (1964)
Republic of Maldives	Libellulidae	*Tramea limbata* (Desjardins, 1832)	1 ♂			Mahlendorf & Martens (2004)
Willis Island, Australia	Libellulidae	*Tramea loewii* Kaup in Brauer, 1866		1		Farrow (1984)
Mexico	Libellulidae	*Tramea onusta* Hagen, 1861			collected at 32 km off shore	Sparks et al. (1986)
India	Libellulidae	*Tramea virginia* (Rambur, 1842)			occasionally at the light source	Andrew & Tembhare (1997)
not specified	Libellulidae	*Tramea* sp.				Campos (1931)
Sudan	Libellulidae	*Trithemis annulata* (Palisot de Beauvois, 1805)				Ris (1924)
French Guyana	Libellulidae	*Zenithoptera fasciata* (Linnaeus, 1758)	1 ♂			Geijskes (1971)
Indone-sia	Libellulidae	*Zyxomma obtusum* Albarda, 1881	♀♀			Lieftinck (1954)
Japan	Libellulidae	*Zyxomma obtusum* Albarda, 1881				Karube (1999)
Japan	Libellulidae	*Zyxomma obtusum* Albarda, 1881	1 ♂			Wada & Inoue (1997)

Counrty	Family	Species	Sex	Σ per site	Notes	Reference
India	Libellulidae	*Zyxomma petiolatum* Rambur, 1842			predominant-ly collected at light source	Andrew & Tembhare (1997)
India	Libellulidae	*Zyxomma petiolatum* Rambur, 1842				Sharma et al. (2000)
Republic of Mauritius	Libellulidae	*Zyxomma petiolatum* Rambur, 1842	1 ♂			Fraser (1950)
Tailand	Libellulidae	*Zyxomma petiolatum* Rambur, 1842				Hämäläinen (1987a)
Mexico	Libellulidae	Libellulidae indet.		2 ind. from 2 sp.	collected at 32 and 160 km distance off the shore	Wolf et al. (1986)
India	Macromiidae	*Epophthalmia frontalis* Selys, 1871				Arulprakash & Gunathilagaraj (2010)
USA		Anisoptera indet		10 sp.		Frost (1970)
Australia		Odonata indet.				Richards & Rowe (1994)
Bulgaria		Odonata indet.				Beshkov (1998)
Germany		Odonata indet.				Löschau (2010)
India		Odonata indet.				Ramamurthy et al. (2010)
New Zealand		Odonata indet.		12		McGregor et al. (1987)
USA		Odonata indet.		11		Frost (1963)
USA		Zygoptera indet.		7 sp.		Frost (1970)
West Is-land, Aldabra Atoll, Indian Ocean		Odonata indet.		5		Frith (1979)

Table 4. A summary of Odonata species ever recorded by light traps.

Suborder	Family	Species	Records
Anisoptera	Libellulidae	*Sympetrum striolatum* (Charpentier, 1840)	23
Anisoptera	Aeshnidae	*Aeshna mixta* Latreille, 1805	19
Anisoptera	Libellulidae	*Pantala flavescens* (Fabricius, 1798)	12
Anisoptera	Aeshnidae	*Anax ephippiger* (Burmeister, 1839)	11
Anisoptera	Libellulidae	*Sympetrum sanguineum* (Müller, 1764)	10
Anisoptera	Aeshnidae	*Anax guttatus* (Burmeister, 1839)	8
Zygoptera	Coenagrionidae	*Enallagma cyathigerum* (Charpentier, 1840)	7
Anisoptera	Aeshnidae	*Aeshna cyanea* (Müller, 1764)	7
Anisoptera	Libellulidae	*Tholymis tillarga* (Fabricius, 1798)	7
Zygoptera	Coenagrionidae	*Ischnura elegans* (Vander Linden, 1820)	6
Anisoptera	Aeshnidae	*Anax junius* (Drury, 1773)	5
Anisoptera	Aeshnidae	*Anax parthenope* (Selys, 1839)	5
Zygoptera	Coenagrionidae	*Ischnura evansi* Morton, 1919	4
Anisoptera	Aeshnidae	*Aeshna grandis* (Linnaeus, 1758)	4
Anisoptera	Aeshnidae	*Anax imperator* Leach, 1815	4
Anisoptera	Aeshnidae	*Gynacantha nervosa* Rambur, 1842	4
Anisoptera	Gomphidae	*Lindenia tetraphylla* (Vander Linden, 1825)	4
Anisoptera	Libellulidae	*Crocothemis servilia* (Drury, 1773)	4
Anisoptera	Libellulidae	*Pachydiplax longipennis* (Burmeister, 1839)	4
Anisoptera	Libellulidae	*Selysiothemis nigra* (Vander Linden, 1825)	4
Anisoptera	Libellulidae	*Sympetrum flaveolum* (Linnaeus, 1758)	4
Anisoptera	Libellulidae	*Sympetrum fonscolombii* (Selys, 1840)	4
Anisoptera	Libellulidae	*Zyxomma petiolatum* Rambur, 1842	4
Zygoptera	Coenagrionidae	*Erythromma viridulum* Charpentier, 1840	3
Zygoptera	Coenagrionidae	*Ischnura ramburii* (Selys in Sagra, 1857)	3
Zygoptera	Lestidae	*Sympecma paedisca* (Brauer, 1877)	3
Anisoptera	Aeshnidae	*Anax tristis* Hagen, 1867	3
Anisoptera	Aeshnidae	*Triacanthagyna septima* (Selys in Sagra, 1857)	3
Anisoptera	Gomphidae	*Ictinogomphus rapax* (Rambur, 1842)	3
Anisoptera	Libellulidae	*Brachythemis contaminata* (Fabricius, 1793)	3
Anisoptera	Libellulidae	*Orthetrum sabina* (Drury, 1770)	3
Anisoptera	Libellulidae	*Zyxomma obtusum* Albarda, 1881	3
Zygoptera	Coenagrionidae	*Cecrion sexlineatum* (Selys, 1883)	2
Zygoptera	Coenagrionidae	*Ceriagrion coromandelianum* (Fabricius, 1798)	2
Zygoptera	Coenagrionidae	*Erythromma najas* (Hansemann, 1823)	2
Zygoptera	Coenagrionidae	*Ischnura posita* (Hagen, 1861)	2
Zygoptera	Coenagrionidae	*Ischnura senegalensis* (Rambur, 1842)	2
Zygoptera	Lestidae	*Indolestes peregrinus* (Ris, 1916)	2
Zygoptera	Lestidae	*Lestes sponsa* (Hansemann, 1823)	2
Zygoptera	Paltycnemididae	*Platycnemis pennipes* (Pallas, 1771)	2
Anisoptera	Aeshnidae	*Aeshna viridis* Eversmann, 1836	2

Suborder	Family	Species	Records
Anisoptera	Aeshnidae	*Anax amazili* (Burmeister, 1839)	2
Anisoptera	Aeshnidae	*Anax immaculifrons* Rambur, 1842	2
Anisoptera	Aeshnidae	*Anax parthenope julius* Brauer, 1865	2
Anisoptera	Aeshnidae	*Coryphaeschna viriditas* Calvert, 1952	2
Anisoptera	Aeshnidae	*Gynacantha hyalina* Selys, 1882	2
Anisoptera	Gomphidae	*Onychogomphus forcipatus* (Linnaeus, 1758)	2
Anisoptera	Libellulidae	*Anatya guttata* (Erichson, 1848)	2
Anisoptera	Libellulidae	*Bradinopyga geminata* (Rambur, 1842)	2
Anisoptera	Libellulidae	*Erythemis simplicicollis* (Say, 1840)	2
Anisoptera	Libellulidae	*Erythrodiplax fusca* (Rambur, 1842)	2
Anisoptera	Libellulidae	*Micrathyria atra* (Martin, 1897)	2
Anisoptera	Libellulidae	*Orthemis ferruginea* (Fabricius, 1775)	2
Anisoptera	Libellulidae	*Pantala hymenaea* Say, 1840	2
Anisoptera	Libellulidae	*Parazyxomma flavicans* (Martin, 1908)	2
Anisoptera	Libellulidae	*Sympetrum danae* (Sulzer, 1776)	2
Anisoptera	Libellulidae	*Sympetrum eroticum* (Selys, 1883)	2
Anisoptera	Libellulidae	*Sympetrum vulgatum* (Linnaeus, 1758)	2
Anisoptera	Libellulidae	*Tramea basilaris* (Palisot de Beauvois, 1805)	2
Zygoptera	Calopterygidae	*Atrocalopteryx atrata* (Selys, 1853)	1
Zygoptera	Calopterygidae	*Hetaerina moribunda* Hagen in Selys, 1853	1
Zygoptera	Calopterygidae	*Vestalaria smaragdina* (Selys, 1879)	1
Zygoptera	Coenagrionidae	*Agriocnemis exilis* Selys, 1872	1
Zygoptera	Coenagrionidae	*Agriocnemis pygmaea* (Rambur, 1842)	1
Zygoptera	Coenagrionidae	*Agriocnemis zerafica* Le Roi, 1915	1
Zygoptera	Coenagrionidae	*Anomalagrion hastatum* (Say, 1839)	1
Zygoptera	Coenagrionidae	*Argia fumipennis* (Burmeister, 1839)	1
Zygoptera	Coenagrionidae	*Austrocnemis maccullochi* (Tillyard, 1926)	1
Zygoptera	Coenagrionidae	*Ceriagrion suave* Ris, 1921	1
Zygoptera	Coenagrionidae	*Coenagrion lanceolatum* (Selys, 1872)	1
Zygoptera	Coenagrionidae	*Enallagma cardenium* Selys, 1876	1
Zygoptera	Coenagrionidae	*Enallagma civile* (Hagen, 1861)	1
Zygoptera	Coenagrionidae	*Enallagma concisum* Williamson, 1922	1
Zygoptera	Coenagrionidae	*Enallagma laurenti* Calvert, 1919	1
Zygoptera	Coenagrionidae	*Homeoura* ? *nepos* (Selys, 1876)	1
Zygoptera	Coenagrionidae	*Ischnura asiatica* (Brauer, 1865)	1
Zygoptera	Coenagrionidae	*Ischnura fountainei* Morton, 1905	1
Zygoptera	Coenagrionidae	*Nehalennia integricollis* Calvert, 1913	1
Zygoptera	Coenagrionidae	*Nehalennia pallidula* Calvert, 1913	1
Zygoptera	Coenagrionidae	*Nehalennia speciosa* (Charpentier, 1840)	1
Zygoptera	Coenagrionidae	*Pseudagrion decorum* (Rambur, 1842)	1
Zygoptera	Coenagrionidae	*Rhodischnura nursei* (Morton, 1907)	1
Zygoptera	Lestidae	*Archilestes grandis* (Rambur, 1942)	1
Zygoptera	Lestidae	*Lestes vidua* Hagen, 1861	1

Suborder	Family	Species	Records
Zygoptera	Lestidae	*Sympecma gobica* Förster, 1900	1
Anisoptera	Aeshnidae	*Anax papuensis* (Burmeister, 1839)	1
Anisoptera	Aeshnidae	*Boyeria irene* (Fonscolombe, 1838)	1
Anisoptera	Aeshnidae	*Boyeria vinosa* (Say, 1840)	1
Anisoptera	Aeshnidae	*Coryphaeschna adnexa* (Hagen, 1861)	1
Anisoptera	Aeshnidae	*Coryphaeschna ingens* (Rambur, 1842)	1
Anisoptera	Aeshnidae	*Epiaeschna heros* (Fabricius, 1798)	1
Anisoptera	Aeshnidae	*Gomphaeschna antilope* (Hagen, 1874)	1
Anisoptera	Aeshnidae	*Gynacantha* ? *dohrni* Krüger, 1899	1
Anisoptera	Aeshnidae	*Gynacantha bayadera* Selys, 1891 (= *G. furcata*?)	1
Anisoptera	Aeshnidae	*Gynacantha bullata* Karsch, 1891	1
Anisoptera	Aeshnidae	*Gynacantha mexicana* Selys, 1868	1
Anisoptera	Aeshnidae	*Gynacantha rammohani* Mitra & Lahiri, 1975	1
Anisoptera	Aeshnidae	*Gynacantha saltatrix* Martin, 1909	1
Anisoptera	Aeshnidae	*Heliaeschna crassa* Krüger, 1899	1
Anisoptera	Aeshnidae	*Indaeschna grubaueri* (Förster, 1904)	1
Anisoptera	Aeshnidae	*Neuraeschna claviforcipata* Martin, 1909	1
Anisoptera	Aeshnidae	*Neuraeschna costalis* (Burmeister, 1839)	1
Anisoptera	Aeshnidae	*Periaeschna laidlawi* (Förster, 1908)	1
Anisoptera	Aeshnidae	*Tetracanthagyna brunnea* McLachlan, 1898	1
Anisoptera	Aeshnidae	*Tetracanthagyna plagiata* (Waterhouse, 1877)	1
Anisoptera	Aeshnidae	*Triacanthagyna trifida* (Rambur, 1842)	1
Anisoptera	Corduliidae	*Austrocordulia refracta* Tillyard, 1909	1
Anisoptera	Corduliidae	*Epitheca cynosura* (Say, 1840)	1
Anisoptera	Corduliidae	*Epitheca princeps* Hagen, 1861	1
Anisoptera	Corduliidae	*Epitheca sepia* (Gloyd, 1933)	1
Anisoptera	Corduliidae	*Hemicordulia gracillima* Fraser, 1944	1
Anisoptera	Corduliidae	*Neurocordulia yamaskanensis* (Provancher, 1875)	1
Anisoptera	Corduliidae	*Oxygastra curtisii* (Dale, 1834)	1
Anisoptera	Gomphidae	*Acrogomphus minor* Laidlaw, 1931	1
Anisoptera	Gomphidae	*Anormogomphus kiritschenkoi* Bartenev, 1913	1
Anisoptera	Gomphidae	*Austrogomphus australis* Dale in Selys, 1854	1
Anisoptera	Gomphidae	*Burmagomphus arthuri* Lieftinck, 1953	1
Anisoptera	Gomphidae	*Cacoides latro* (Erichson, 1848)	1
Anisoptera	Gomphidae	*Gomphus flavipes lineatus* Bartenev, 1929	1
Anisoptera	Gomphidae	*Ictinogomphus decoratus melaenops* Selys, 1857	1
Anisoptera	Gomphidae	*Macrogomphus parallelogramma parallelogramma* (Burmeister, 1839)	1
Anisoptera	Gomphidae	*Melanocacus mungo* (Needham, 1940)	1
Anisoptera	Gomphidae	*Notogomphus lujai* (Schouteden, 1934)	1
Anisoptera	Gomphidae	*Onychogomphus flexuosus* (Schneider, 1845)	1
Anisoptera	Gomphidae	*Ophiogomphus reductus* Calvert, 1898	1
Anisoptera	Gomphidae	*Paragomphus cognatus* (Rambur, 1842)	1

Suborder	Family	Species	Records
Anisoptera	Gomphidae	*Paragomphus lineatus* (Selys, 1850)	1
Anisoptera	Gomphidae	*Paragomphus pumilio* (Rambur, 1842)	1
Anisoptera	Gomphidae	*Phyllogomphoides andromeda* (Selys, 1869)	1
Anisoptera	Gomphidae	*Phyllogomphoides fuliginosus* (Hagen in Selys, 1854)	1
Anisoptera	Gomphidae	*Phyllogomphoides selysi* (Navás, 1924)	1
Anisoptera	Gomphidae	*Phyllogomphus selysi* Schouteden, 1933	1
Anisoptera	Gomphidae	*Progomphus brachycnemis* Needham, 1944	1
Anisoptera	Gomphidae	*Sinictinogomphus clavatus* (Fabricius, 1775)	1
Anisoptera	Libellulidae	*Aethriamanta rezia* Kirby, 1889	1
Anisoptera	Libellulidae	*Brachymesia furcata* (Hagen, 1861)	1
Anisoptera	Libellulidae	*Brachymesia herbida* (Gundlach, 1889)	1
Anisoptera	Libellulidae	*Brachythemis leucosticta* (Burmeister, 1839)	1
Anisoptera	Libellulidae	*Camacinia gigantea* (Brauer, 1867)	1
Anisoptera	Libellulidae	*Celithemis eponina* (Drury, 1773)	1
Anisoptera	Libellulidae	*Celithemis ornata* (Rambur, 1842)	1
Anisoptera	Libellulidae	*Chalcostephia flavifrons* Kirby, 1889	1
Anisoptera	Libellulidae	*Crocothemis erythraea* (Brullé, 1832)	1
Anisoptera	Libellulidae	*Crocothemis sanguinolenta* (Burmeister, 1839)	1
Anisoptera	Libellulidae	*Diplacodes lefebvrii* (Rambur, 1842)	1
Anisoptera	Libellulidae	*Diplacodes luminans* (Karsch, 1893)	1
Anisoptera	Libellulidae	*Diplacodes trivialis* (Rambur, 1842)	1
Anisoptera	Libellulidae	*Erythrodiplax famula* (Erichson, 1848)	1
Anisoptera	Libellulidae	*Erythrodiplax haematogastra* (Burmeister, 1839)	1
Anisoptera	Libellulidae	*Erythrodiplax longitudinalis* (Ris, 1919)	1
Anisoptera	Libellulidae	*Erythrodiplax minuscula* (Rambur, 1842)	1
Anisoptera	Libellulidae	*Erythrodiplax umbrata* (Linnaeus, 1758)	1
Anisoptera	Libellulidae	*Hemistigma albipuncta* (Rambur, 1842)	1
Anisoptera	Libellulidae	*Leucorrhinia pectoralis* (Charpentier, 1825)	1
Anisoptera	Libellulidae	*Libellula auripennis* Burmeister, 1839	1
Anisoptera	Libellulidae	*Libellula axilena* Westwood, 1837	1
Anisoptera	Libellulidae	*Libellula quadrimaculata* Linnaeus, 1758	1
Anisoptera	Libellulidae	*Macrodiplax cora* (Kaup in Brauer, 1867)	1
Anisoptera	Libellulidae	*Micrathyria aequalis* (Hagen, 1861)	1
Anisoptera	Libellulidae	*Micrathyria laevigata* Calvert, 1909	1
Anisoptera	Libellulidae	*Micrathyria mengeri* Ris, 1919	1
Anisoptera	Libellulidae	*Micrathyria ocellata* Martin, 1897	1
Anisoptera	Libellulidae	*Nephepeltia flavifrons* (Karsch, 1889)	1
Anisoptera	Libellulidae	*Neurothemis tullia tullia* (Drury, 1773)	1
Anisoptera	Libellulidae	*Notiothemis robertsi* Fraser, 1944	1
Anisoptera	Libellulidae	*Olpogastra lugubris* (Karsch, 1895)	1
Anisoptera	Libellulidae	*Orthemis sulphurata* Hagen, 1868	1
Anisoptera	Libellulidae	*Orthetrum* ? *guineense* Ris, 1909	1
Anisoptera	Libellulidae	*Orthetrum* ? *trinacria* (Selys, 1841)	1

Suborder	Family	Species	Records
Anisoptera	Libellulidae	*Orthetrum brachiale* (Palisot de Beauvois, 1805)	1
Anisoptera	Libellulidae	*Orthetrum brunneum* (Fonscolombe, 1837)	1
Anisoptera	Libellulidae	*Orthetrum camerunense* Gambles, 1959	1
Anisoptera	Libellulidae	*Orthetrum cancellatum* (Linnaeus, 1758)	1
Anisoptera	Libellulidae	*Orthetrum chrysostigma* (Burmeister, 1839)	1
Anisoptera	Libellulidae	*Orthetrum hintzi* Schmidt, 1951	1
Anisoptera	Libellulidae	*Orthetrum icteromelas cinctifrons* Pinhey, 1970	1
Anisoptera	Libellulidae	*Orthetrum julia* Kirby, 1900	1
Anisoptera	Libellulidae	*Orthetrum triangulare melania*(Selys, 1883)	1
Anisoptera	Libellulidae	*Palpopleura portia* (Drury, 1773)	1
Anisoptera	Libellulidae	*Perithemis mooma* Kirby, 1889	1
Anisoptera	Libellulidae	*Perithemis tenera* (Say, 1840)	1
Anisoptera	Libellulidae	*Pornothemis serrata* Krüger, 1902	1
Anisoptera	Libellulidae	*Sympetrum ambiguum* (Rambur, 1842)	1
Anisoptera	Libellulidae	*Sympetrum arenicolor* Jödicke, 1994	1
Anisoptera	Libellulidae	*Sympetrum depressiusculum* (Selys, 1841)	1
Anisoptera	Libellulidae	*Sympetrum vulgatum decoratum* Selys, 1884	1
Anisoptera	Libellulidae	*Tauriphila australis* (Hagen, 1867)	1
Anisoptera	Libellulidae	*Tholymis citrina* Hagen, 1867	1
Anisoptera	Libellulidae	*Tramea basilaris burmeisteri* Kirby, 1889	1
Anisoptera	Libellulidae	*Tramea calverti* Muttkowski, 1910	1
Anisoptera	Libellulidae	*Tramea carolina* (Linnaeus, 1763)	1
Anisoptera	Libellulidae	*Tramea limbata* (Desjardins, 1832)	1
Anisoptera	Libellulidae	*Tramea loewii* Kaup in Brauer, 1866	1
Anisoptera	Libellulidae	*Tramea onusta* Hagen, 1861	1
Anisoptera	Libellulidae	*Tramea virginia* (Rambur, 1842)	1
Anisoptera	Libellulidae	*Trithemis annulata* (Palisot de Beauvois, 1805)	1
Anisoptera	Libellulidae	*Zenithoptera fasciata* (Linnaeus, 1758)	1
Anisoptera	Macromiidae	*Epophthalmia frontalis* Selys, 1871	1